Efficient Aerodynamic Simulation of Multi-rotor Vehicles

Jonathan Chiew
NASA Ames Research Center
Stanford University

Michael Aftosmis
NASA Ames Research Center


NASA: Lillian Gipson

Future Concept Vehicles in Urban Airspaces







Complex Aerodynamics for Multi-rotor Vehicles






Unsteady rotary-wing aerodynamics

Propulsor-airframe interaction

Trim algorithms

Complex geometry

Low Reynolds numbers

Aeroacoustics

Outline

Introduction & Motivation

Aerodynamics & Rotor Model

Mesh Convergence & Scalability

Trim Algorithms

Validation Cases

Conclusions & Outlook

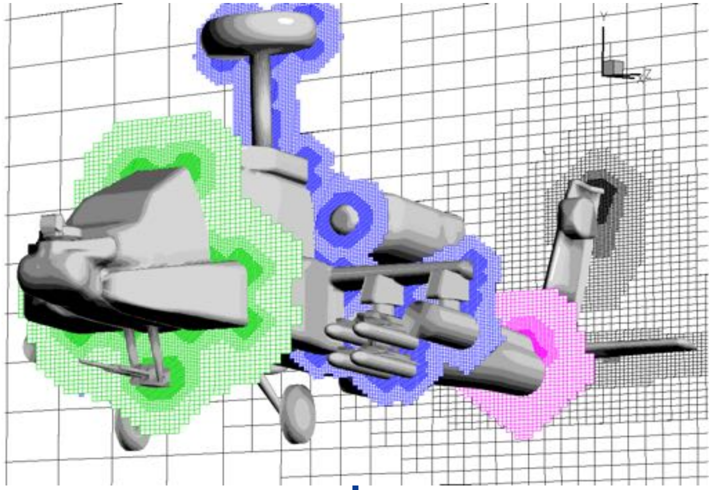
Technical Approach

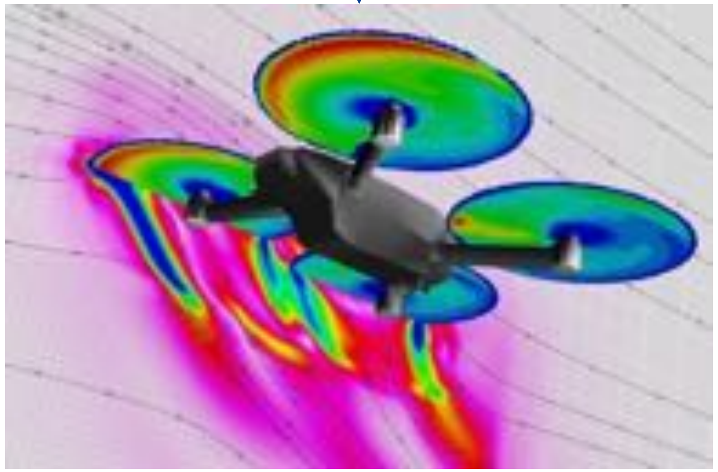
GOAL: Single- and multi-rotor vehicle performance estimates with reasonable turnaround time on modest compute resources

NASA's Cart3D software

- Multigrid accelerated Euler solver (inviscid flow)
- Cartesian mesh with embedded boundaries
- Automated meshing for arbitrarily complex geometry
- 2^{nd} order spatial and temporal accuracy
- Adjoint-based mesh adaptation
- Domain decomposition for excellent scalability

Requires addition of a rotor model





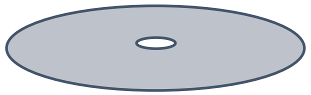
Rotor Modeling Approaches

Include rotating blades in CFD solution

- High-fidelity, physics-resolving simulations (OVERFLOW-2, Helios, etc.)
- Time-accurate computations are expensive
- Viscous effects needed to predict torque and power consumption

Momentum and Energy Source-Term Model

- Model the rotor's effect with source terms in the governing equations
- Blade forces computed using Blade Element Theory
- No re-meshing required – unified approach for steady and unsteady simulations

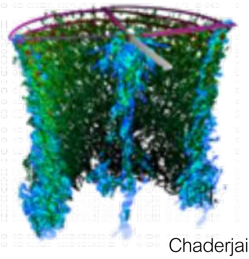


Uniform Actuator Disk | Blade Element Momentum Theory | Lifting-line | ?? | CFD – DES/LES

lower fidelity
lower cost

Aerodynamic Models

higher fidelity
higher cost



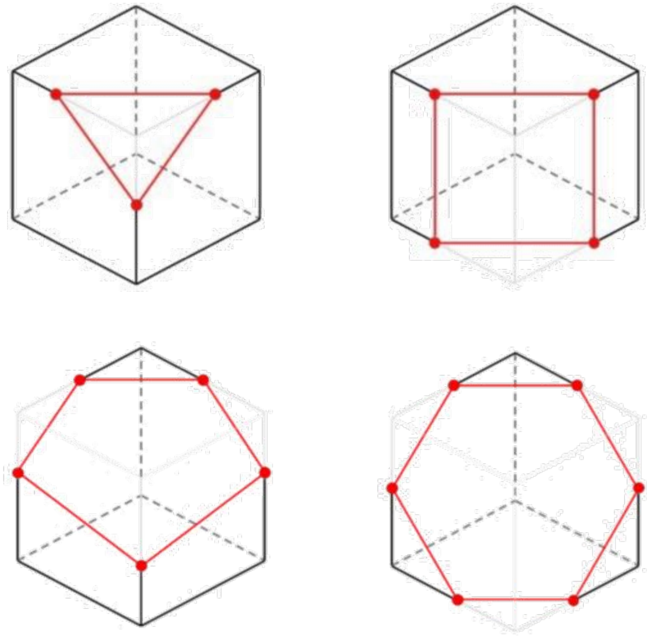
Chaderjain & Ahmad

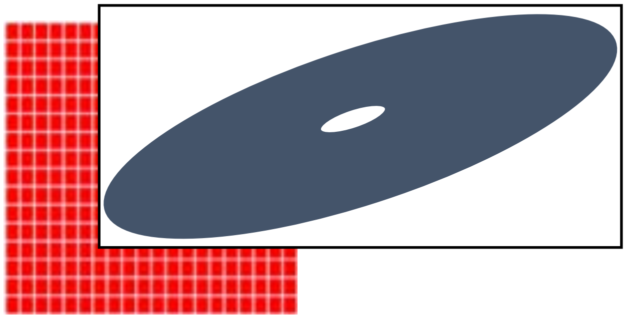
Rotor Modeling on Cartesian Meshes

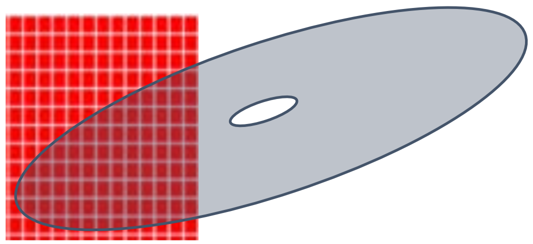
Use Cartesian hexahedra directly vs embedded polar grid

Find cells intersecting the rotor disk denoted “rotor hexes”

Use bounding box to eliminate majority of hexahedra



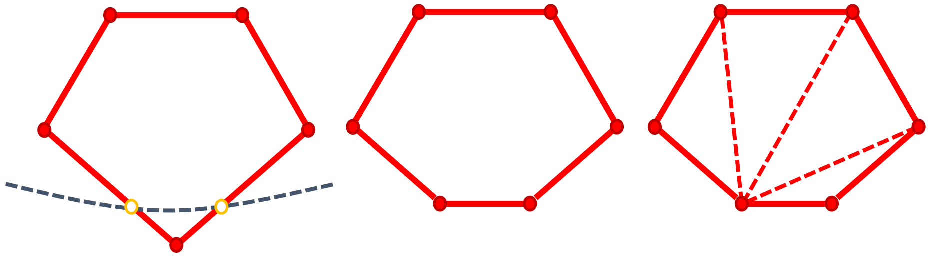




Compute intersection of cell with rotor plane

Linearly clip cells to lie entirely inside the disk

Calculate centroid and area of polygon via tessellation

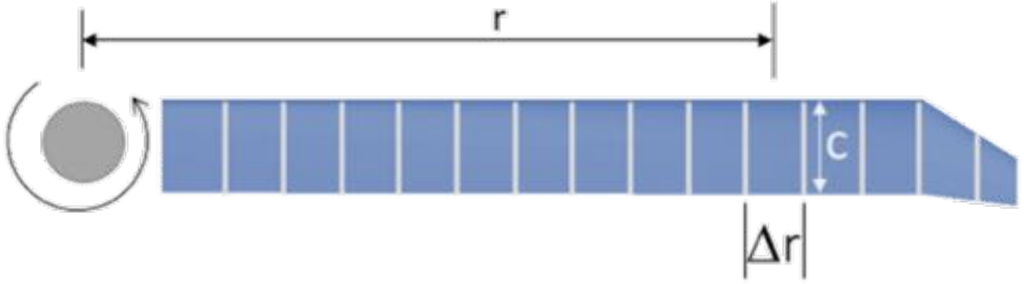


Blade Element Theory

Divide blade into spanwise sections

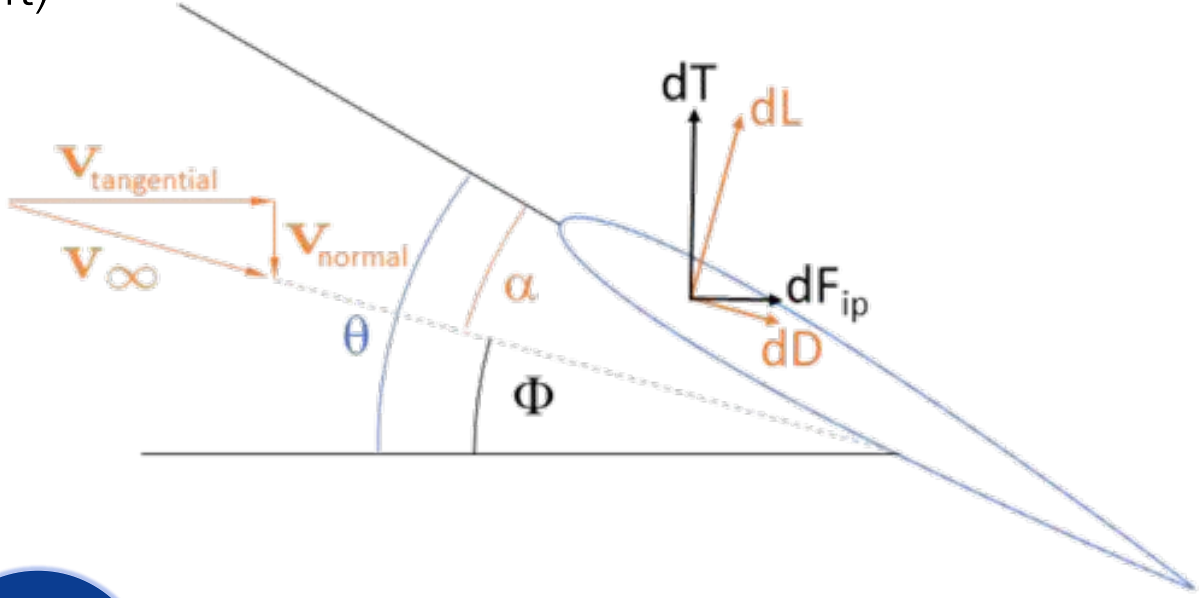
2-dimensional aerodynamics using table lookups based on CFD velocity field

Sectional lift and drag forces are then rotated into the desired axes (Cartesian or rotor shaft)



$$dL = \frac{1}{2}\rho \left|\mathbf{v}_\infty\right|^2 c_l c \Delta r$$

$$dD = \frac{1}{2}\rho \left|\mathbf{v}_\infty\right|^2 c_d c \Delta r$$



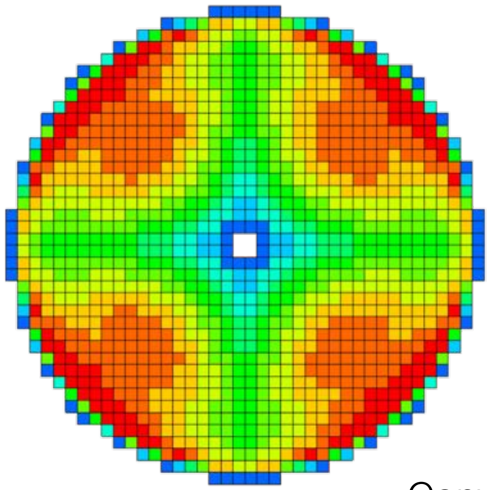
Rotor Force Distribution

Forces from each blade are scaled by the time it spends inside each cell

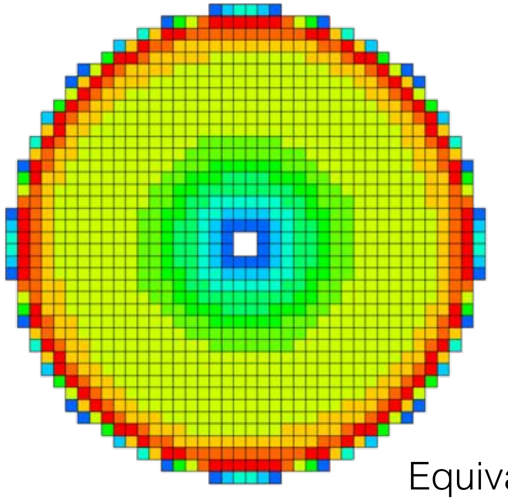
Models in literature typically use the angular width of the cell for the scaling

The conventional approach gives a poor force distribution on Cartesian meshes

Use radius of circle with equivalent area to scale forces and maintain axisymmetry



Conventional



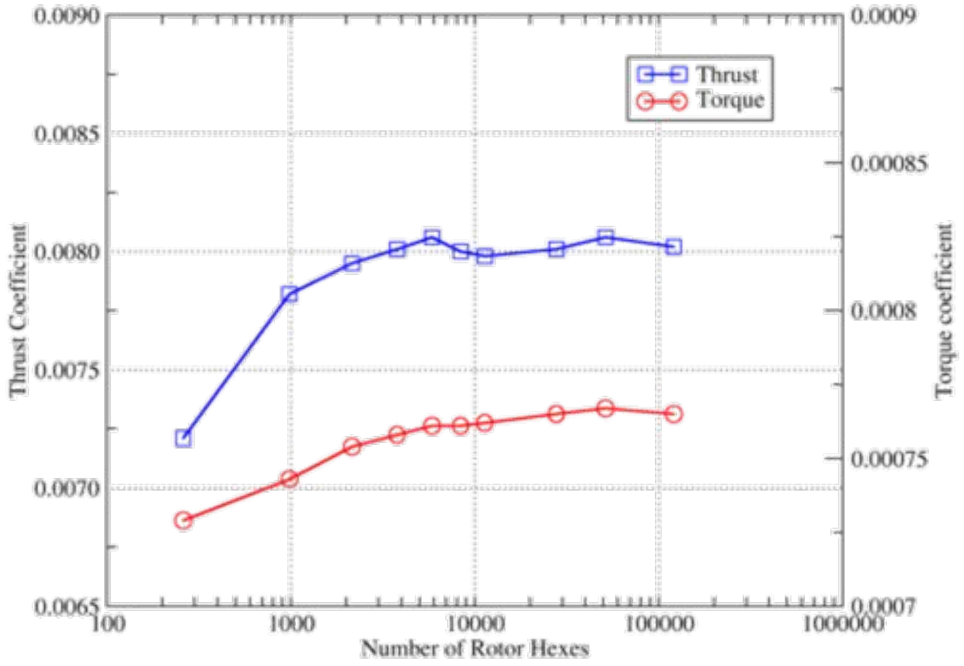
Equivalent Area

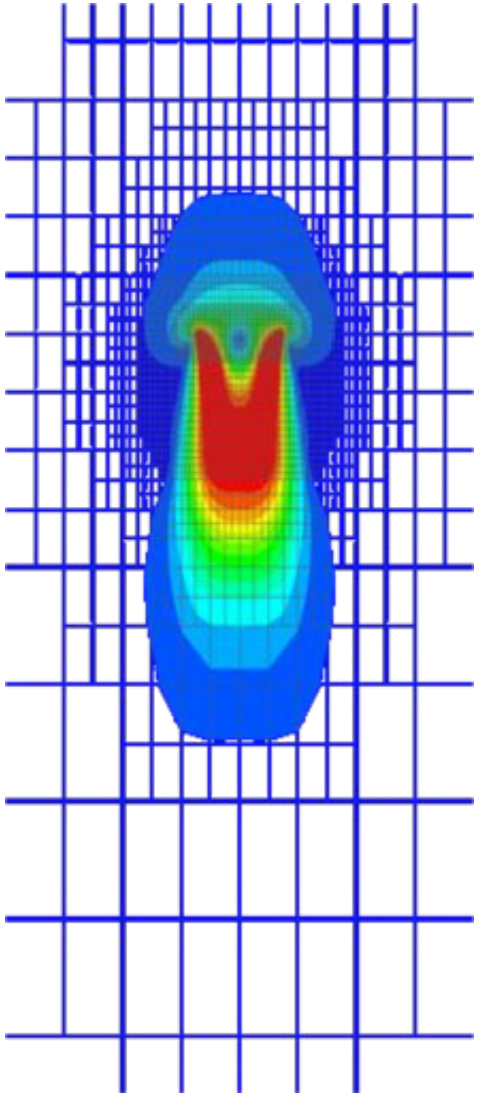
Mesh Convergence Study

Simple rotor – untwisted, constant chord, 12% thick airfoil

Tip Mach = 0.69, Collective pitch = 10°

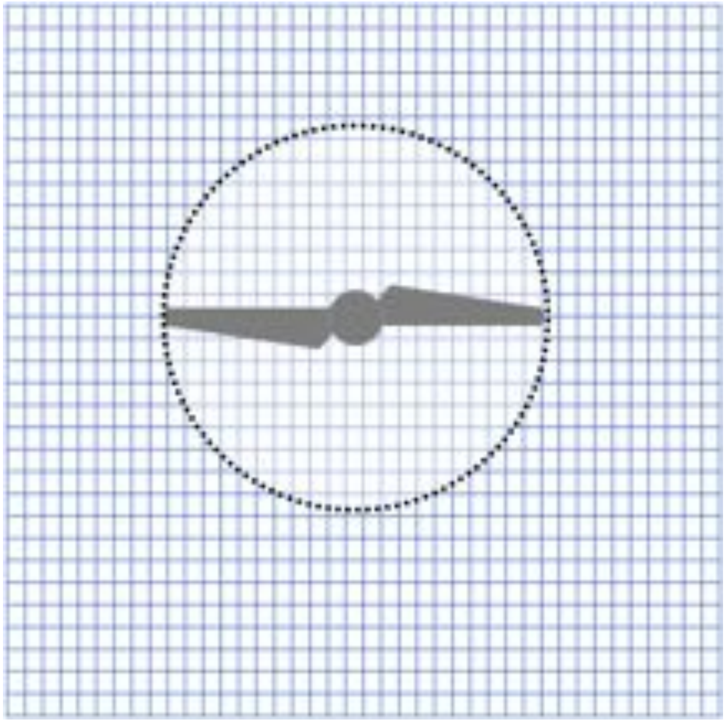
Farfield boundaries at 60R (lateral) or 120R (vertical)

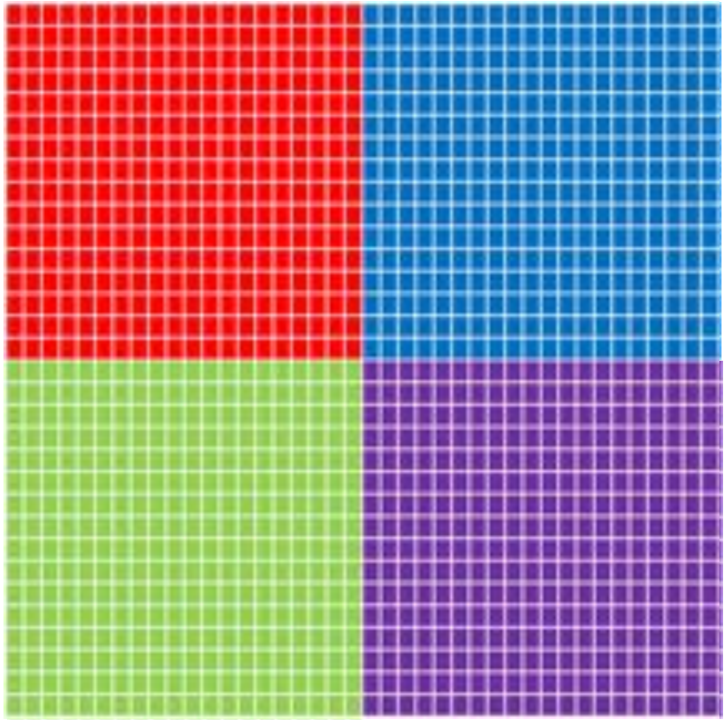




Rotor Model Parallelization

The rotor hex search is performed in parallel on all partitions in one pre-processing step

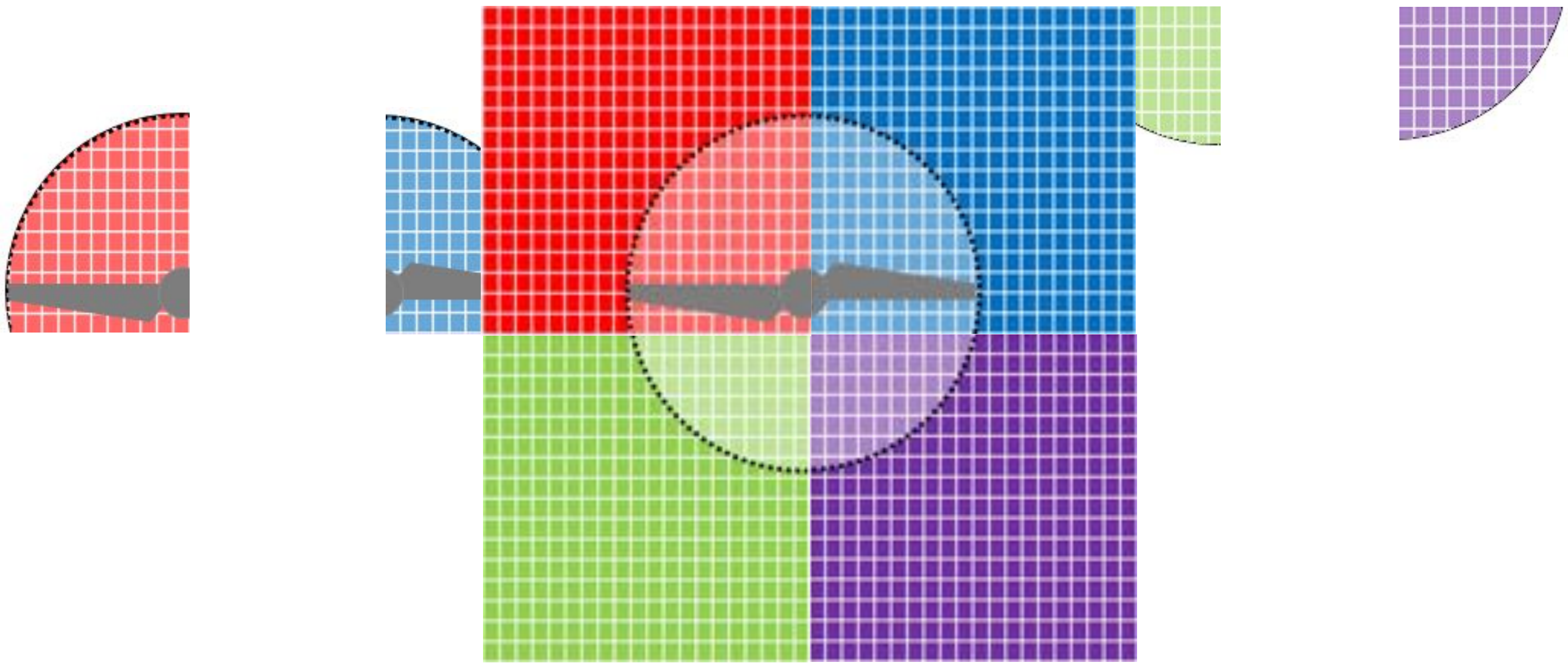




Domain Decomposition

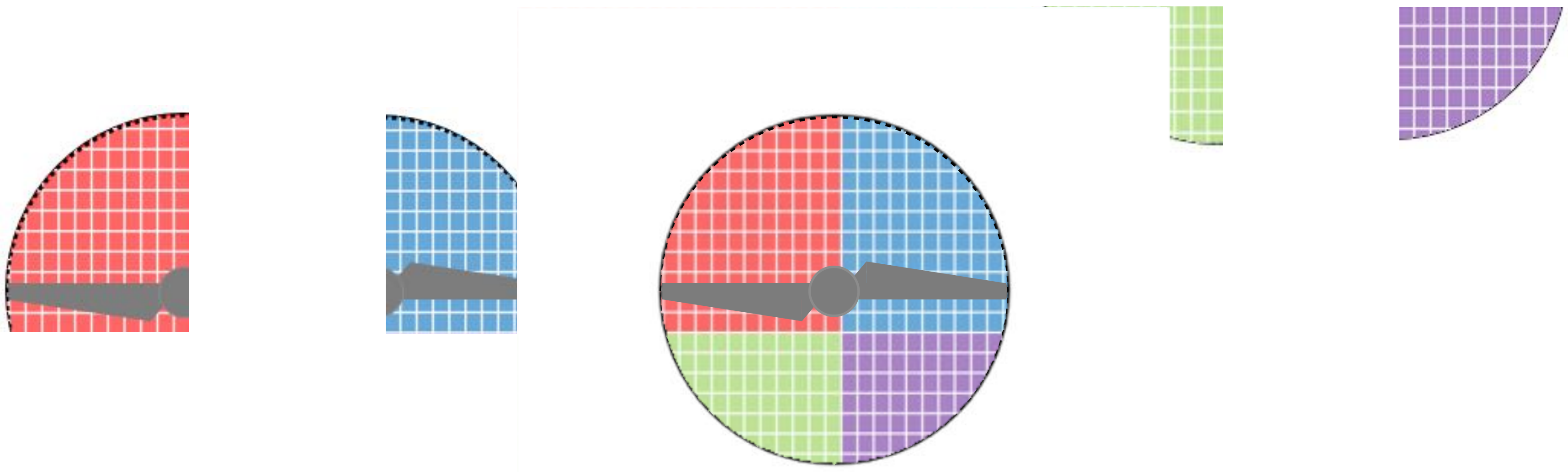
Rotor Model Parallelization

The rotor hex search is performed in parallel on all partitions in one pre-processing step



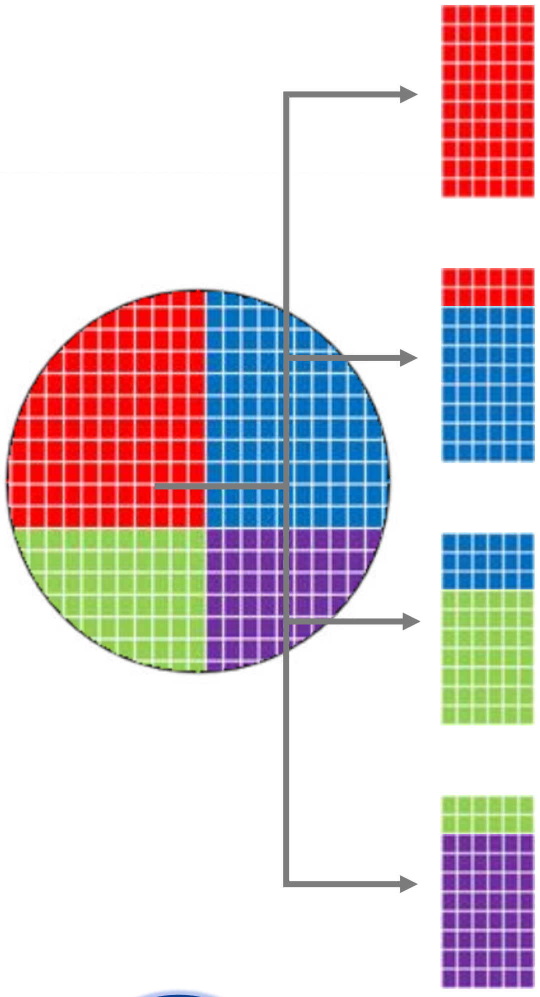
Rotor Model Parallelization

The rotor hex search is performed in parallel on all partitions in one pre-processing step



Rotor Model Parallelization

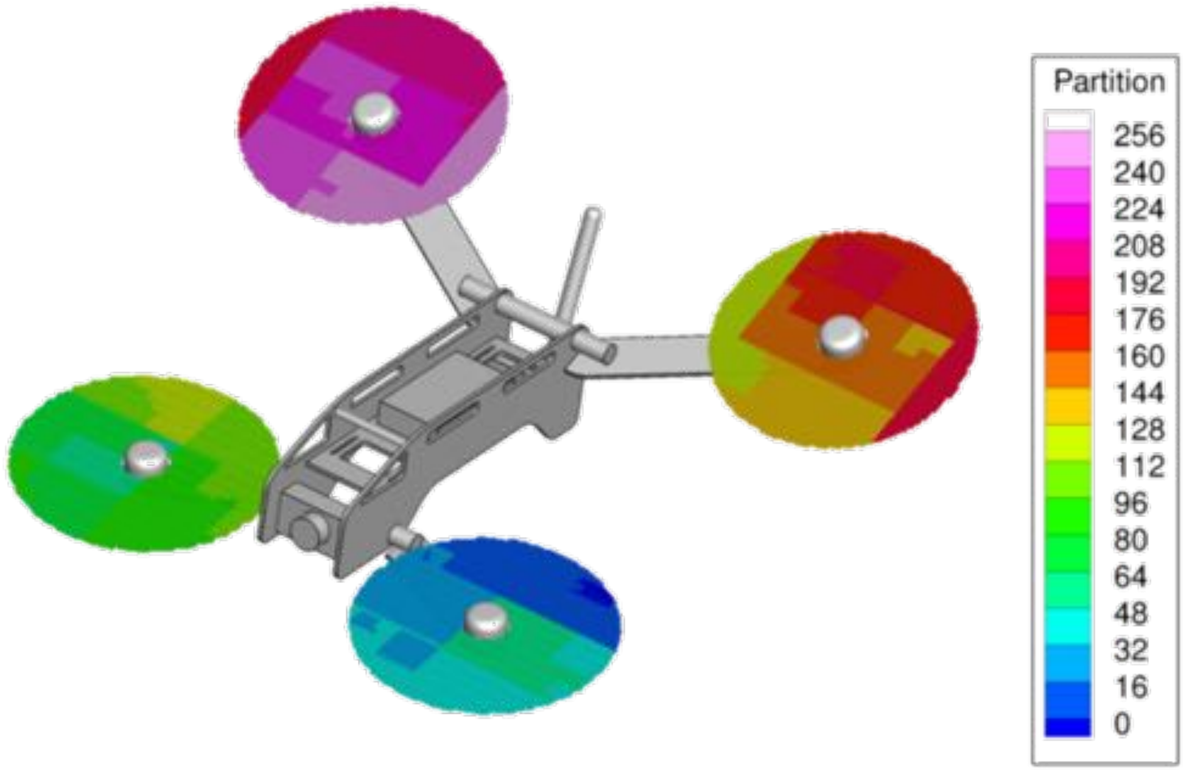
Hexes from all rotors are distributed equally among all partitions to ensure scalability

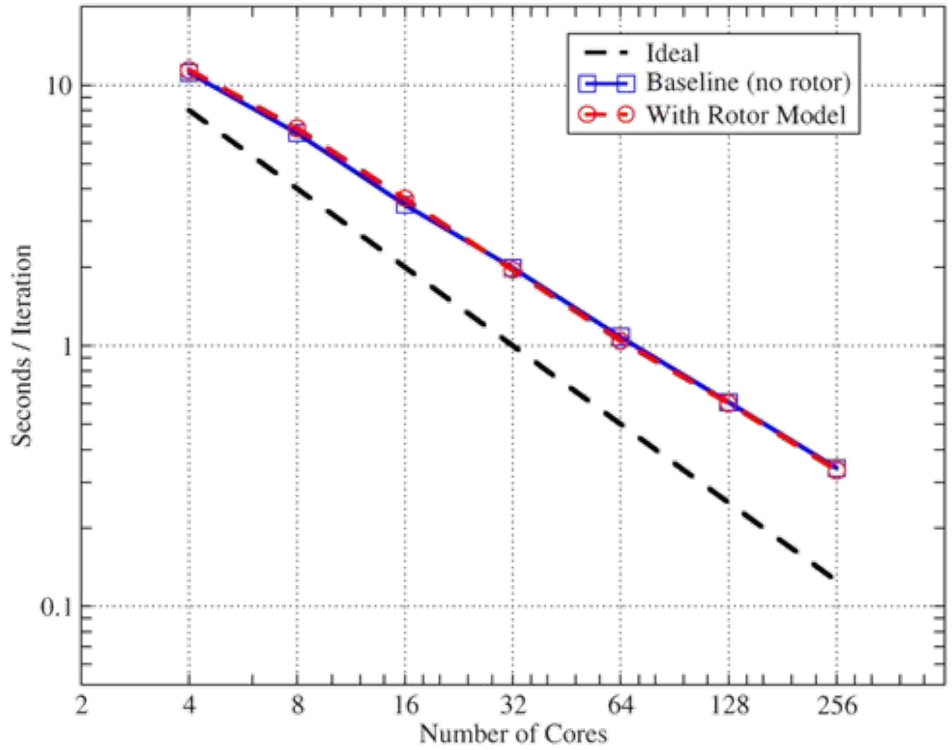


Parallelization: Strong Scaling

Parallel implementation preserves scalability of baseline solver

Speedup is linear with respect to number of processors





Validation Study: XV-15

3-bladed proprotor

-40.9° twist

NACA 64-XXX airfoil sections

Compare to flight test data

Hover

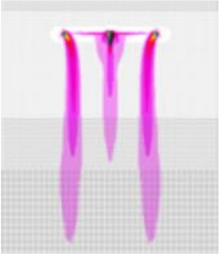
- Isolated rotor
- OARF data

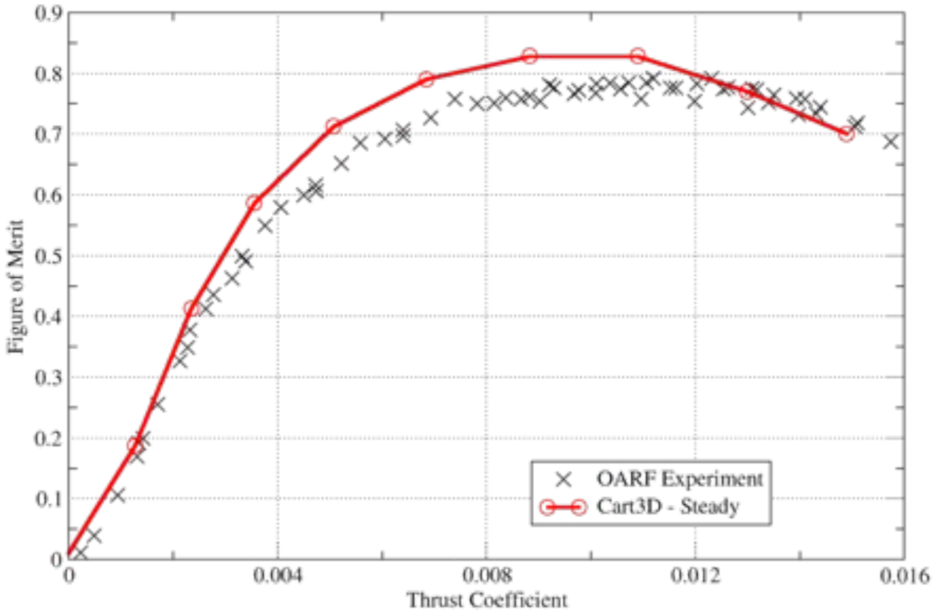
Edgewise Forward Flight

- Rotor with Rotor Test Apparatus (RTA)
- NFAC data (two tests)

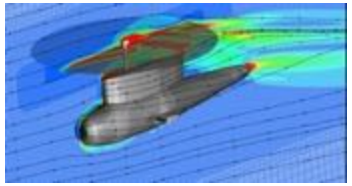
Validation Study: XV-15 Rotor

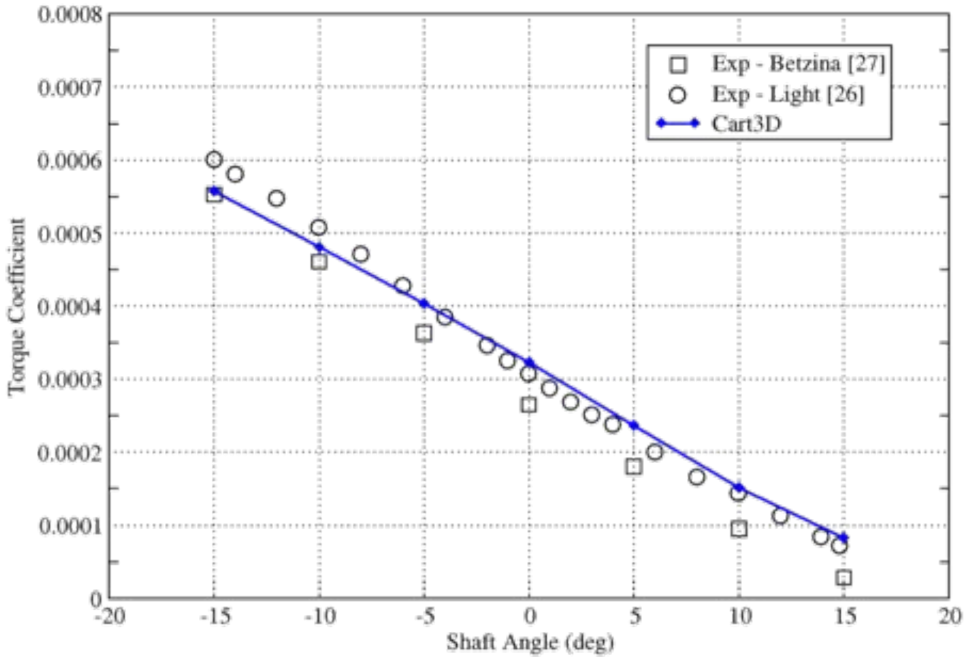
Hover - Isolated Rotor

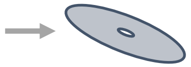




Forward Flight



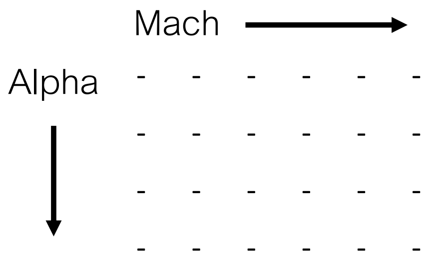




Low Reynolds Number Aerodynamics

Python-based tool to combine 2-D airfoil performance data from various sources:

- Flat plate theory
- Wind tunnel experiments
- XFOIL / RANS



Creates standard C81 format (or custom regularized) airfoil tables that include Reynolds number effects in the Mach number dependency

Requires multiple tables for each airfoil for tapered blades to account for variations in chord length

Very similar to general procedure of Russell and Sekula

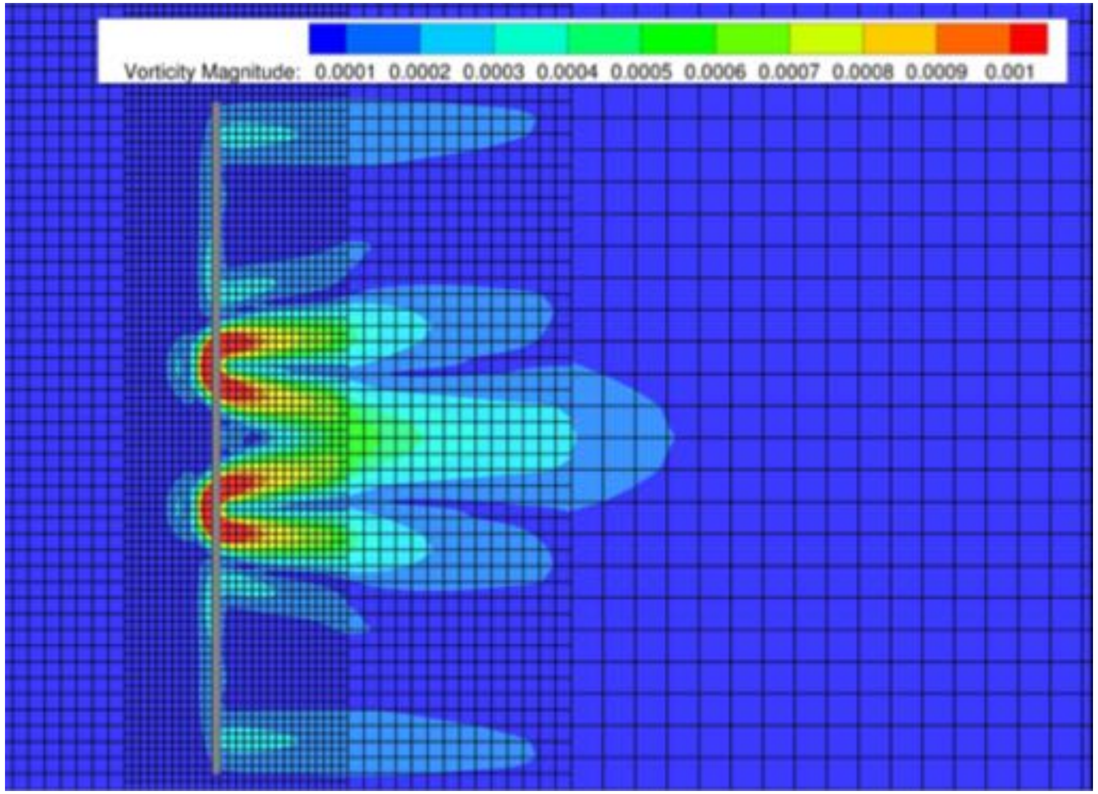
Validation Study: APC 10-inch Propellers

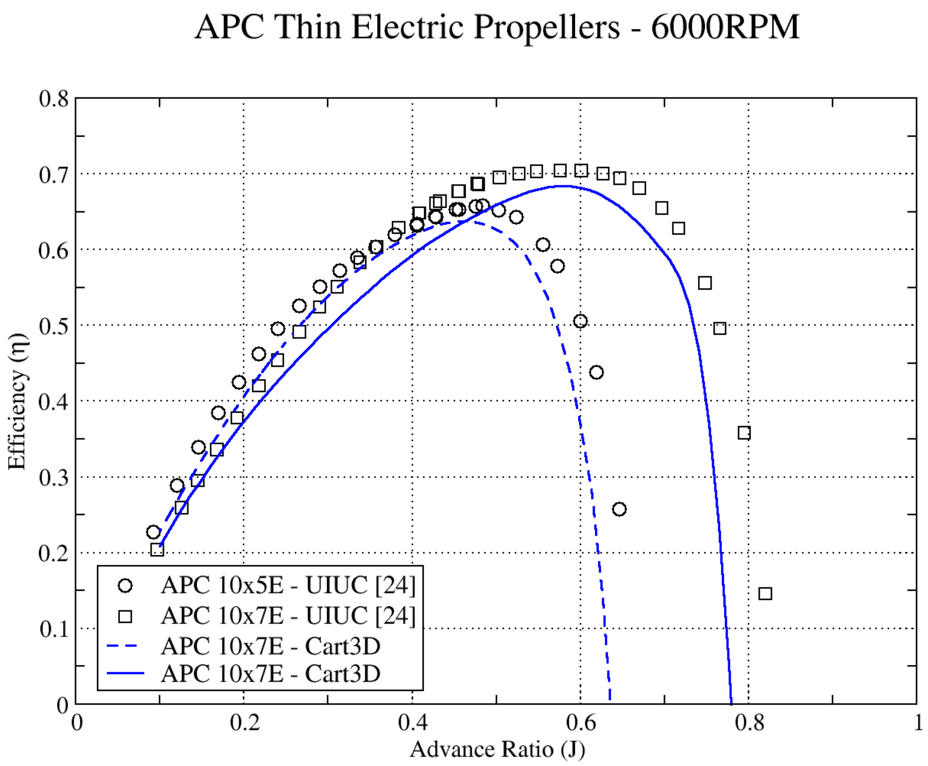
	APC 10x5E			APC 10x7E		
r/R	Airfoil	Twist (deg)	Chord (c/R)	Airfoil	Twist (deg)	Chord (c/R)
0.2	NACA 5521	37.19	0.139	NACA 4521	45.82	0.154
0.3	NACA 4515	29.25	0.189	NACA 5515	38.35	0.190
0.4	NACA 5513	22.54	0.201	NACA 5514	29.90	0.202
0.5	NACA 5513	18.46	0.194	NACA 5513	24.67	0.195
0.6	NACA 4512	15.97	0.174	NACA 4412	20.88	0.174
0.7	NACA 4511	14.09	0.135	NACA 4411	17.98	0.135
0.8	NACA 4410	12.84	0.112	NACA 4410	15.79	0.112
0.9	NACA 4309	11.37	0.081	NACA 4409	13.86	0.081
1.0	NACA 4309	8.99	0.041	NACA 4309	11.53	0.040

Brandt et al. (UIUC - propDB), MacNeill et al. (Aeronautical Journal, 2017)

Validation Study: APC 10-inch Propellers

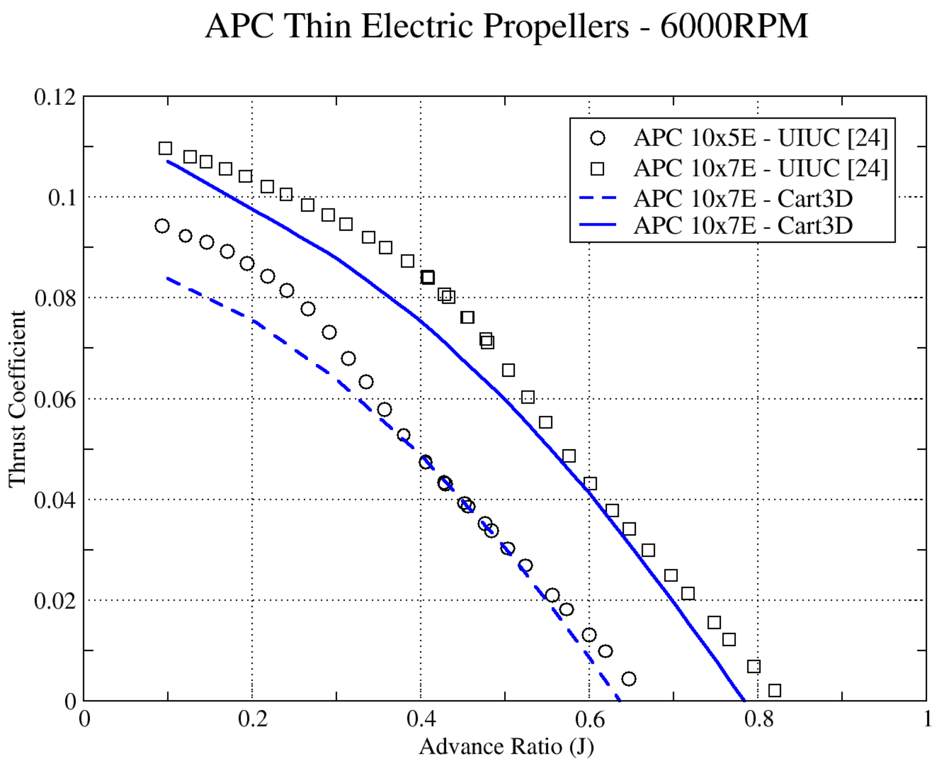
APC 10x5E – J = 0.55

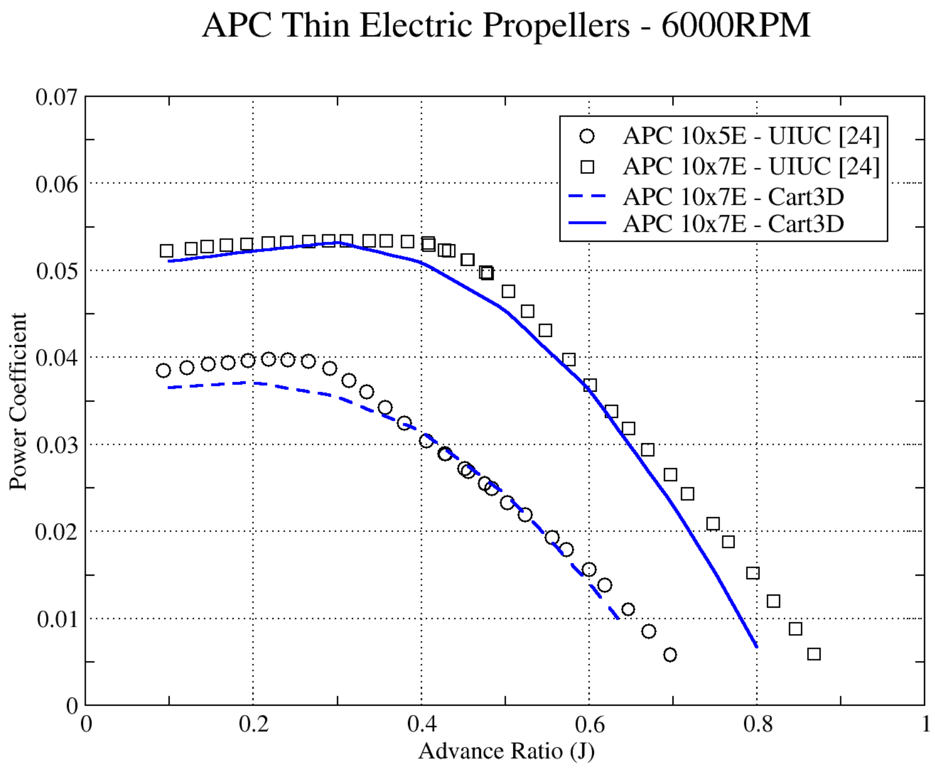




2 million cells – 6 minutes/case on 1 Skylake node

Validation Study: APC 10-inch Propellers





Aircraft Trim and Forward Flight

Variety of configurations with different control surfaces

For rotor-borne flight, trim essential for performance estimates

Vehicles often overactuated for safety, but not always

Requires a general trim algorithm

Start with simple cases

- Single rotor
- Quadrotor

Forward Flight Trim

Example: helicopter trim with collective and cyclic pitch

Linearize the trim equations

$$\begin{bmatrix} C_T \\ C_{RM} \\ C_{PM} \end{bmatrix}^i + \begin{bmatrix} \frac{\partial C_T}{\partial \theta_{75}} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{RM}}{\partial \theta_{75}} & \frac{\partial C_{RM}}{\partial \theta_{1c}} & \frac{\partial C_{RM}}{\partial \theta_{1s}} \\ \frac{\partial C_{PM}}{\partial \theta_{75}} & \frac{\partial C_{PM}}{\partial \theta_{1c}} & \frac{\partial C_{PM}}{\partial \theta_{1s}} \end{bmatrix} \begin{bmatrix} \Delta\theta_{75} \\ \Delta\theta_{1c} \\ \Delta\theta_{1s} \end{bmatrix} = \begin{bmatrix} C_{T,tgt} \\ 0 \\ 0 \end{bmatrix}$$

Forward Flight Trim

Compute the Jacobian matrix with finite differences of the control inputs

Assume an instantaneously frozen flow field

$$\begin{bmatrix} \frac{\partial C_T}{\partial \theta_{75}} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{RM}}{\partial \theta_{75}} & \frac{\partial C_{RM}}{\partial \theta_{1c}} & \frac{\partial C_{RM}}{\partial \theta_{1s}} \\ \frac{\partial C_{PM}}{\partial \theta_{75}} & \frac{\partial C_{PM}}{\partial \theta_{1c}} & \frac{\partial C_{PM}}{\partial \theta_{1s}} \end{bmatrix}$$

Forward Flight Trim

Solve the linear system to get control input updates

In-place LU factorization with partial pivoting

$$\begin{bmatrix} \frac{\partial C_T}{\partial \theta_{75}} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{RM}}{\partial \theta_{75}} & \frac{\partial C_{RM}}{\partial \theta_{1c}} & \frac{\partial C_{RM}}{\partial \theta_{1s}} \\ \frac{\partial C_{PM}}{\partial \theta_{75}} & \frac{\partial C_{PM}}{\partial \theta_{1c}} & \frac{\partial C_{PM}}{\partial \theta_{1s}} \end{bmatrix} \begin{bmatrix} \Delta\theta_{75} \\ \Delta\theta_{1c} \\ \Delta\theta_{1s} \end{bmatrix} = \begin{bmatrix} C_{T,tgt} - C_T \\ -C_{RM} \\ -C_{PM} \end{bmatrix}$$

Forward Flight Trim

Newton's Method to remove the linearization errors

Stops when tolerances are satisfied or maximum number of iterations reached

$$\begin{bmatrix} \frac{\partial C_T}{\partial \theta_{75}} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{RM}}{\partial \theta_{75}} & \frac{\partial C_{RM}}{\partial \theta_{1c}} & \frac{\partial C_{RM}}{\partial \theta_{1s}} \\ \frac{\partial C_{PM}}{\partial \theta_{75}} & \frac{\partial C_{PM}}{\partial \theta_{1c}} & \frac{\partial C_{PM}}{\partial \theta_{1s}} \end{bmatrix} \begin{bmatrix} \Delta\theta_{75} \\ \Delta\theta_{1c} \\ \Delta\theta_{1s} \end{bmatrix} = \begin{bmatrix} C_{T,tgt} - C_T \\ -C_{RM} \\ -C_{PM} \end{bmatrix}$$

Helicopter Forward Flight Trim

Follow the approach of Yang et al.

Three control inputs: collective pitch, lateral and longitudinal cyclic pitch

Specify rotor thrust

Zero pitch and roll moments

$$\begin{bmatrix} C_T \\ C_{RM} \\ C_{PM} \end{bmatrix}^i + \begin{bmatrix} \frac{\partial C_T}{\partial \theta_{75}} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{RM}}{\partial \theta_{75}} & \frac{\partial C_{RM}}{\partial \theta_{1c}} & \frac{\partial C_{RM}}{\partial \theta_{1s}} \\ \frac{\partial C_{PM}}{\partial \theta_{75}} & \frac{\partial C_{PM}}{\partial \theta_{1c}} & \frac{\partial C_{PM}}{\partial \theta_{1s}} \end{bmatrix} \begin{bmatrix} \Delta\theta_{75} \\ \Delta\theta_{1c} \\ \Delta\theta_{1s} \end{bmatrix} = \begin{bmatrix} C_{T,tgt} \\ 0 \\ 0 \end{bmatrix}$$

Quadcopter Forward Flight Trim

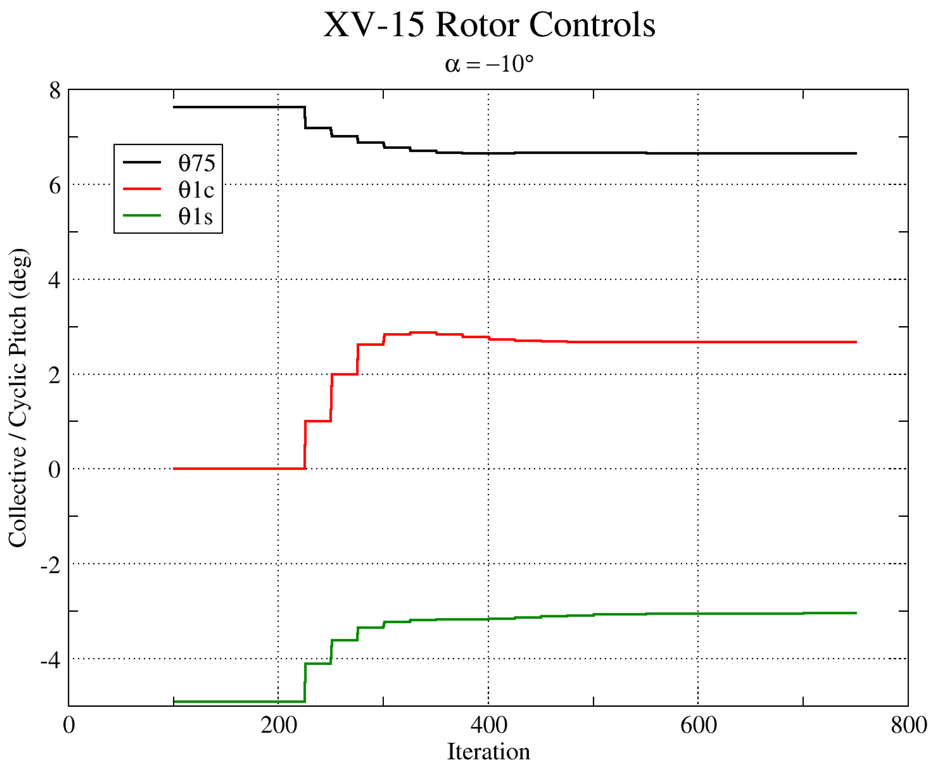
Four control inputs: rotational speed of each propeller

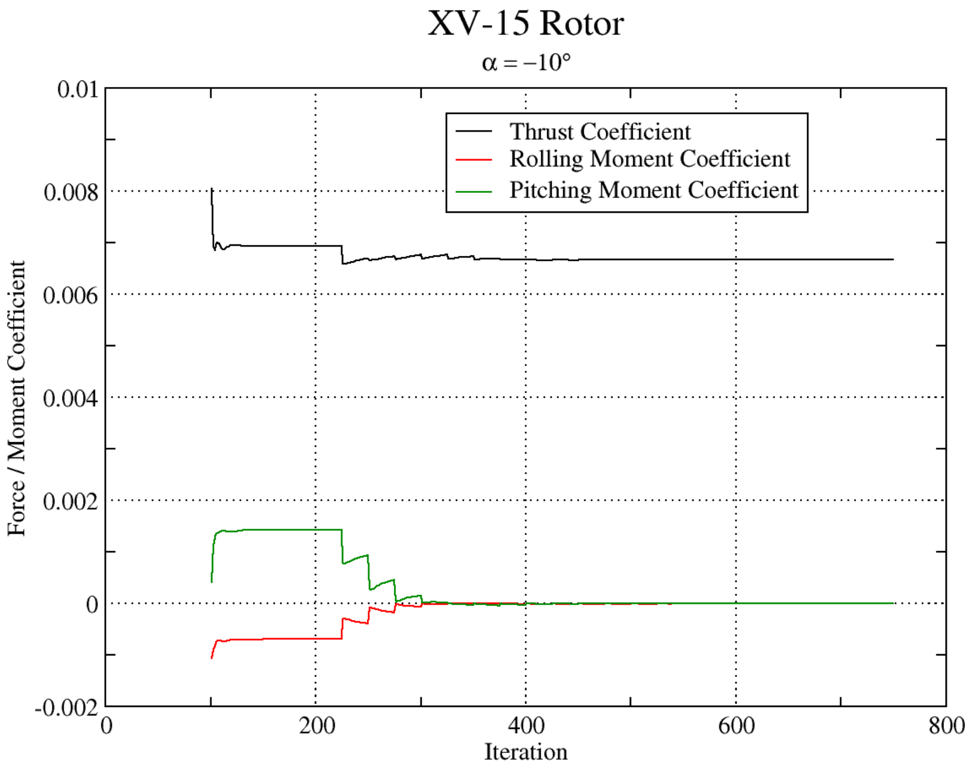
Specify total lift force

Zero pitch, roll, and yaw moments

$$\begin{bmatrix} C_W \\ C_{RM} \\ C_{PM} \\ C_Q \end{bmatrix}^i + \begin{bmatrix} \frac{\partial C_W}{\partial \Omega_1} & \frac{\partial C_W}{\partial \Omega_2} & \frac{\partial C_W}{\partial \Omega_3} & \frac{\partial C_W}{\partial \Omega_4} \\ \frac{\partial C_{RM}}{\partial \Omega_1} & \frac{\partial C_{RM}}{\partial \Omega_2} & \frac{\partial C_{RM}}{\partial \Omega_3} & \frac{\partial C_{RM}}{\partial \Omega_4} \\ \frac{\partial C_{PM}}{\partial \Omega_1} & \frac{\partial C_{PM}}{\partial \Omega_2} & \frac{\partial C_{PM}}{\partial \Omega_3} & \frac{\partial C_{PM}}{\partial \Omega_4} \\ \frac{\partial C_Q}{\partial \Omega_1} & \frac{\partial C_Q}{\partial \Omega_2} & \frac{\partial C_Q}{\partial \Omega_3} & \frac{\partial C_Q}{\partial \Omega_4} \end{bmatrix} \begin{bmatrix} \Delta\Omega_1 \\ \Delta\Omega_2 \\ \Delta\Omega_3 \\ \Delta\Omega_4 \end{bmatrix} = \begin{bmatrix} C_{W,tgt} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

XV-15 Rotor Trim



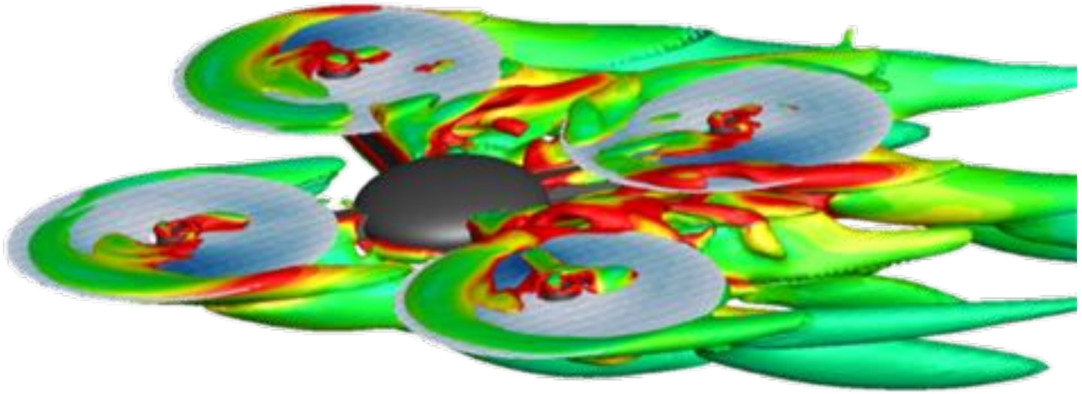


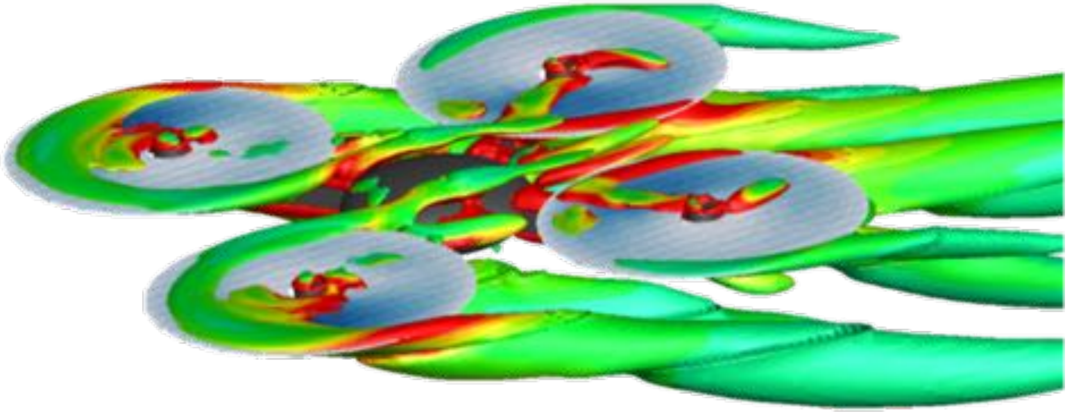
Multi-Rotor Performance

Performance of multi-rotor vehicles influenced by rotor-rotor interactions

Can be beneficial (side-by-side) or detrimental

Wake trajectories different between hover and forward flight





Rotor-Rotor Aerodynamic Interactions

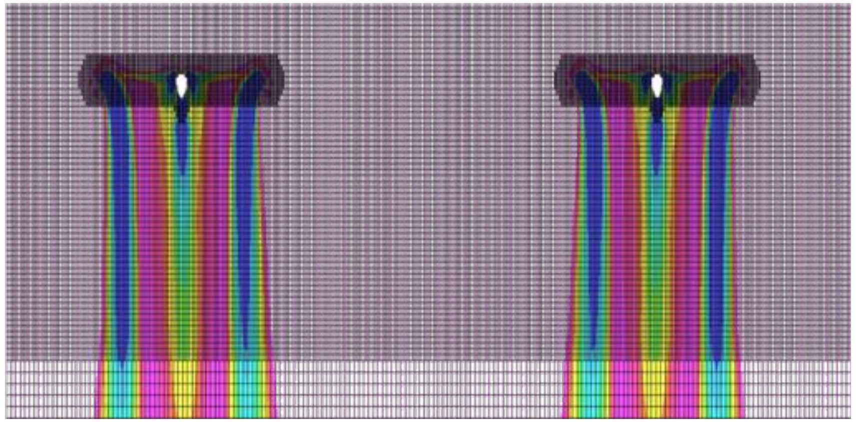
4 XV-15 rotors in Hover

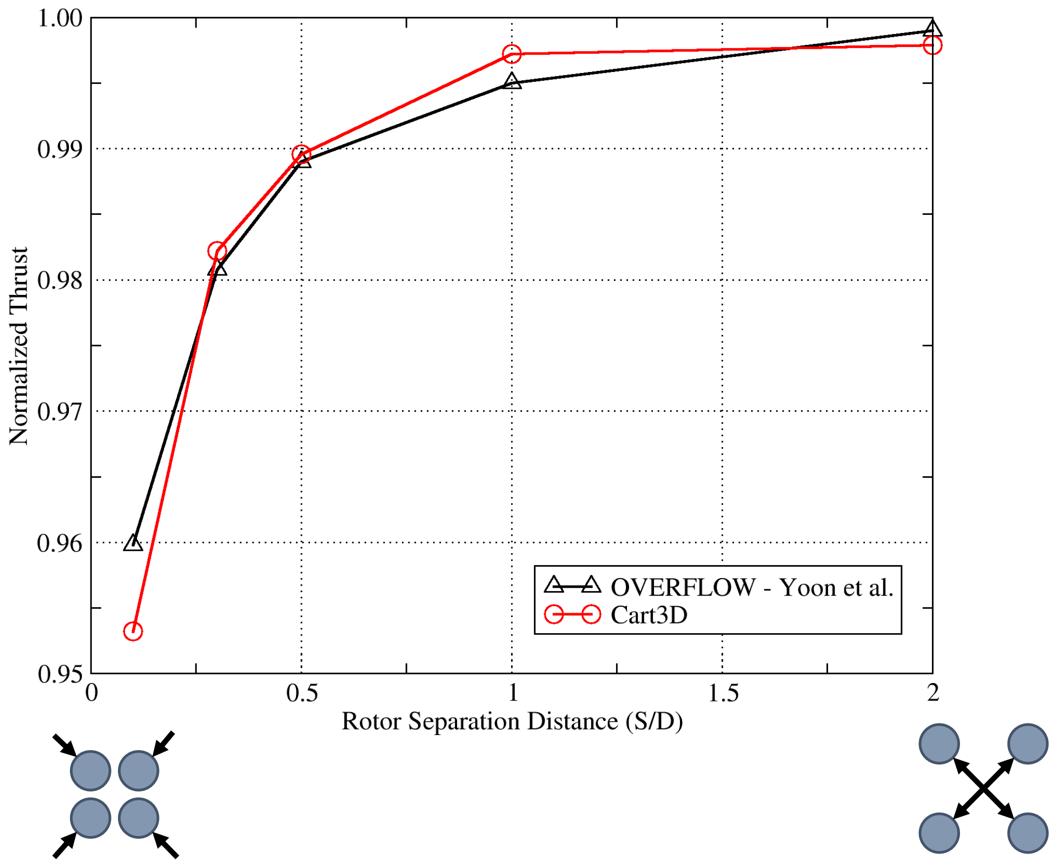
Tip Mach = 0.69

Collective pitch 10°

Vary separation distance

Comparison to high-fidelity OVERFLOW results of Yoon, et al.





Rotor-Rotor Aerodynamic Interactions

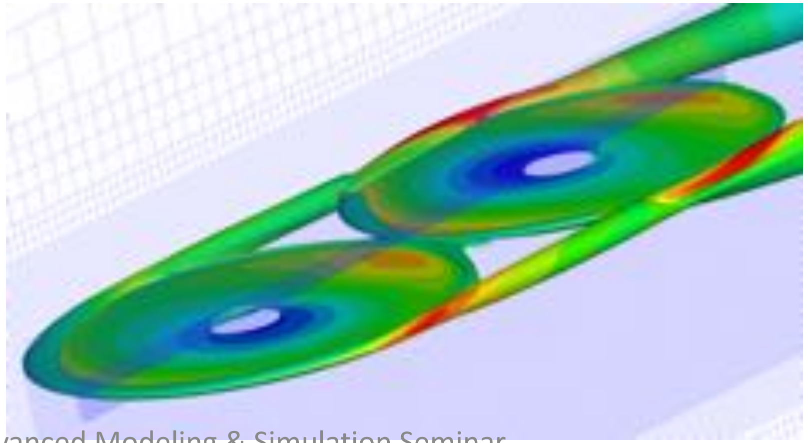
15 ft diameter rotors in Tandem

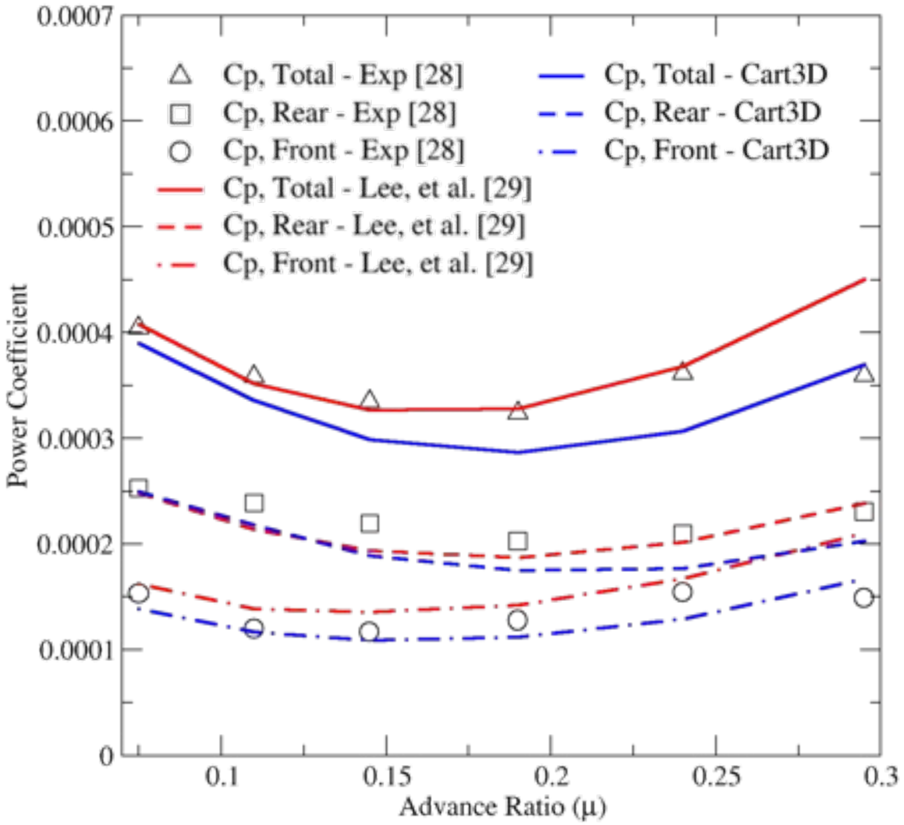
NACA 0012, untwisted, untapered blades

Separation distance of 1.03 diameters

Rotors trimmed sequentially

Compare to Langley wind tunnel test (1954) and panel method + free wake (Lee, 2009)





Representative Quadcopter Study

Ellipsoidal centerbody

Square cross-sectional arms

Cylindrical motors

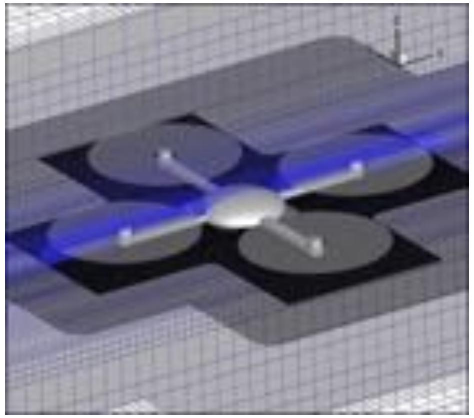
450mm frame size

(4) APC 10x5 propellers

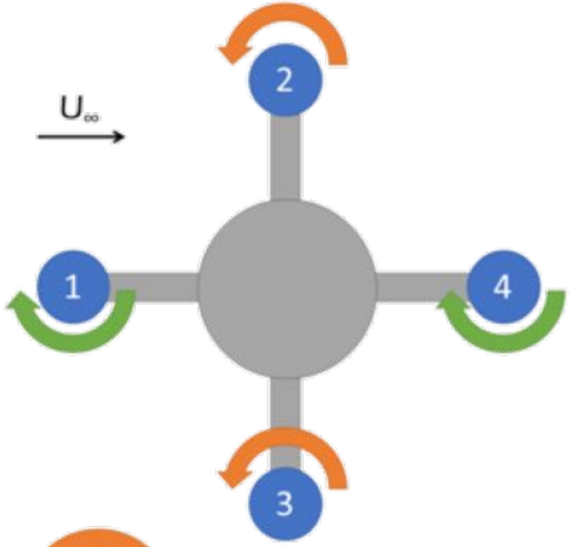
6000 RPM (baseline)

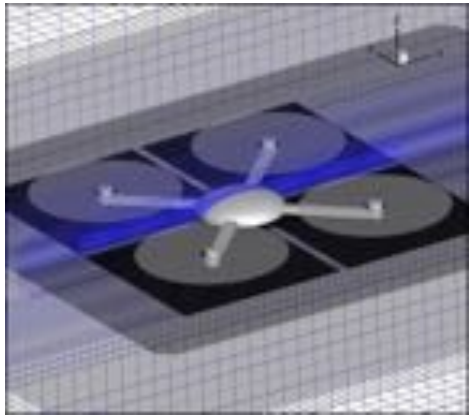
6 million cells

45 min on 1 Skylake node

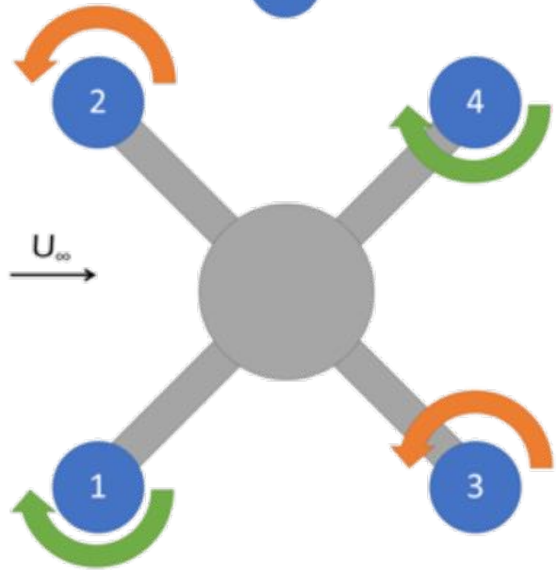


'+' configuration

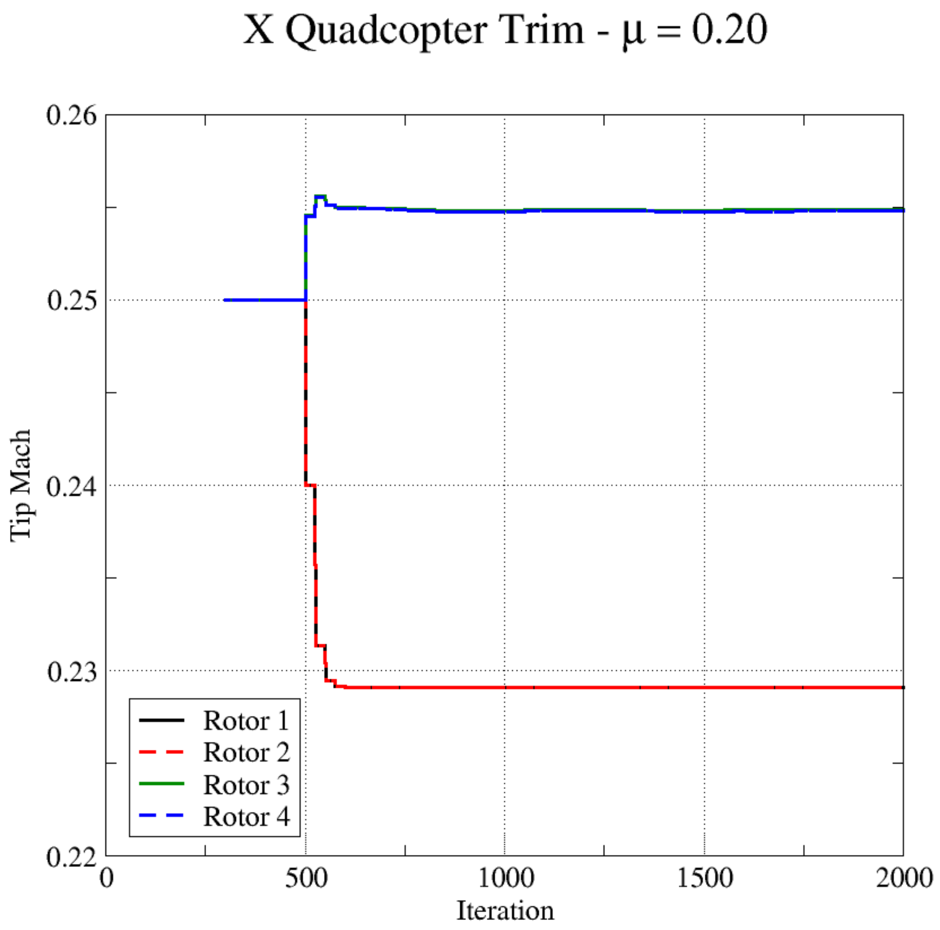


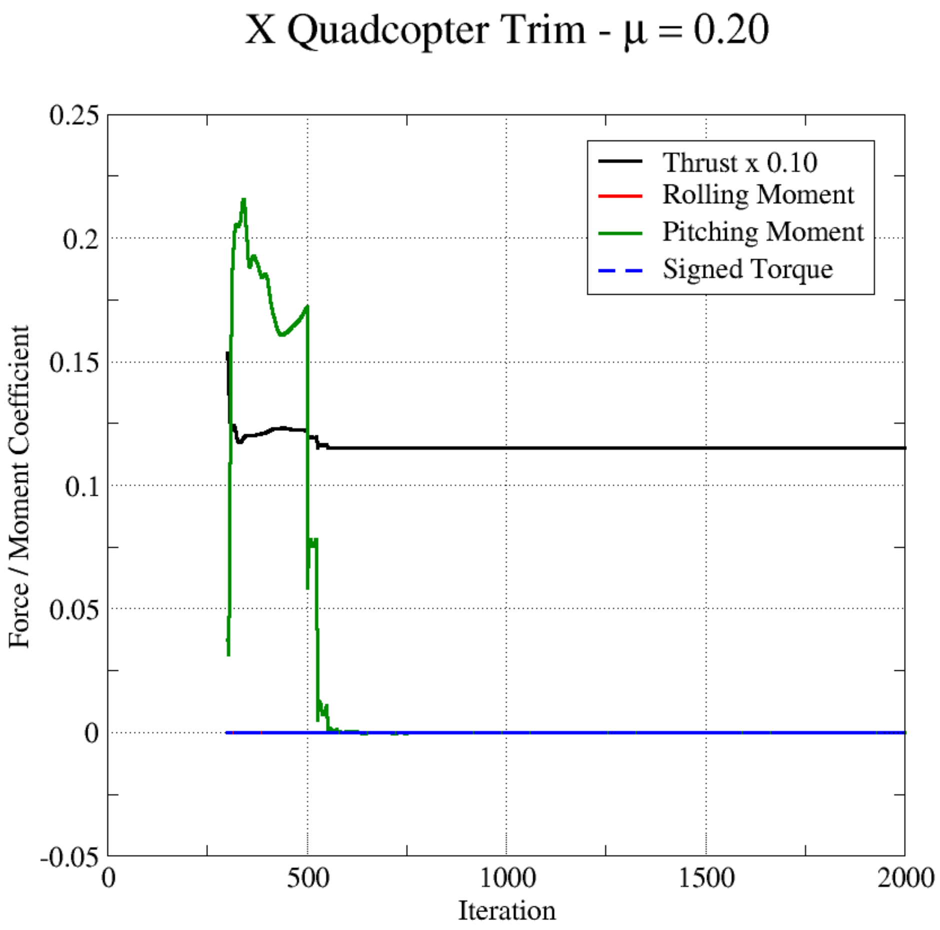


'x' configuration

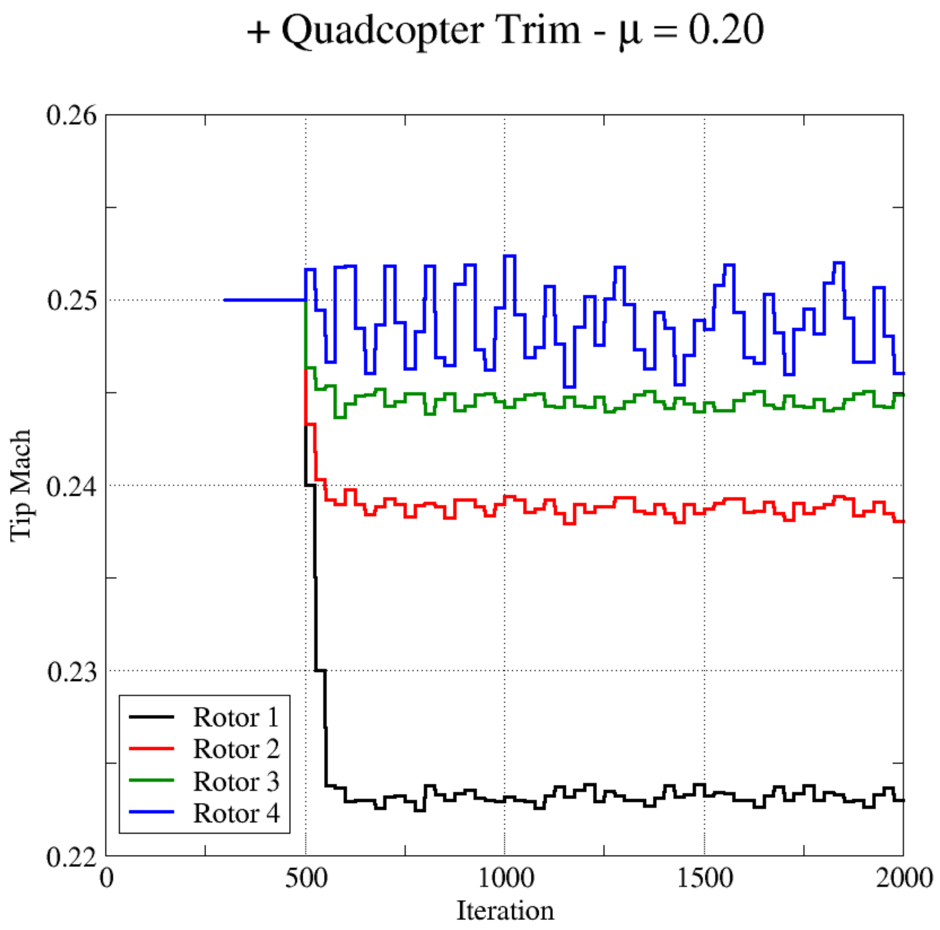


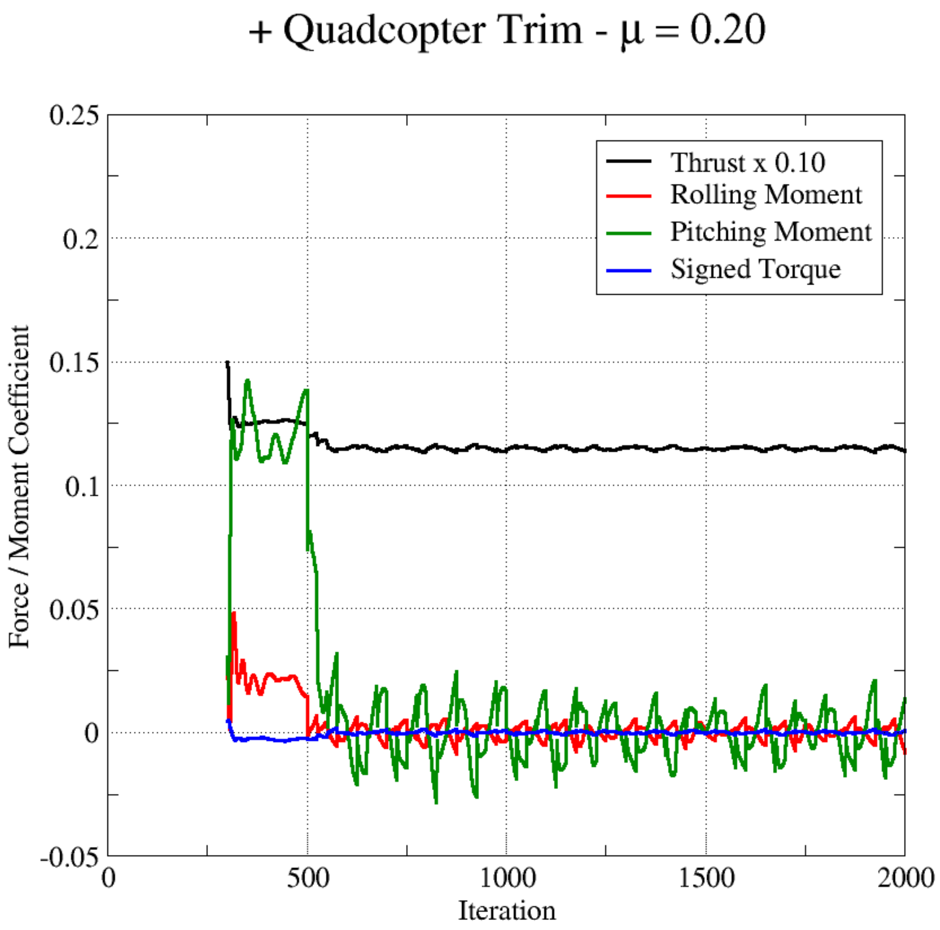
Quadcopter Trim: x configuration





Quadcopter Trim: + configuration



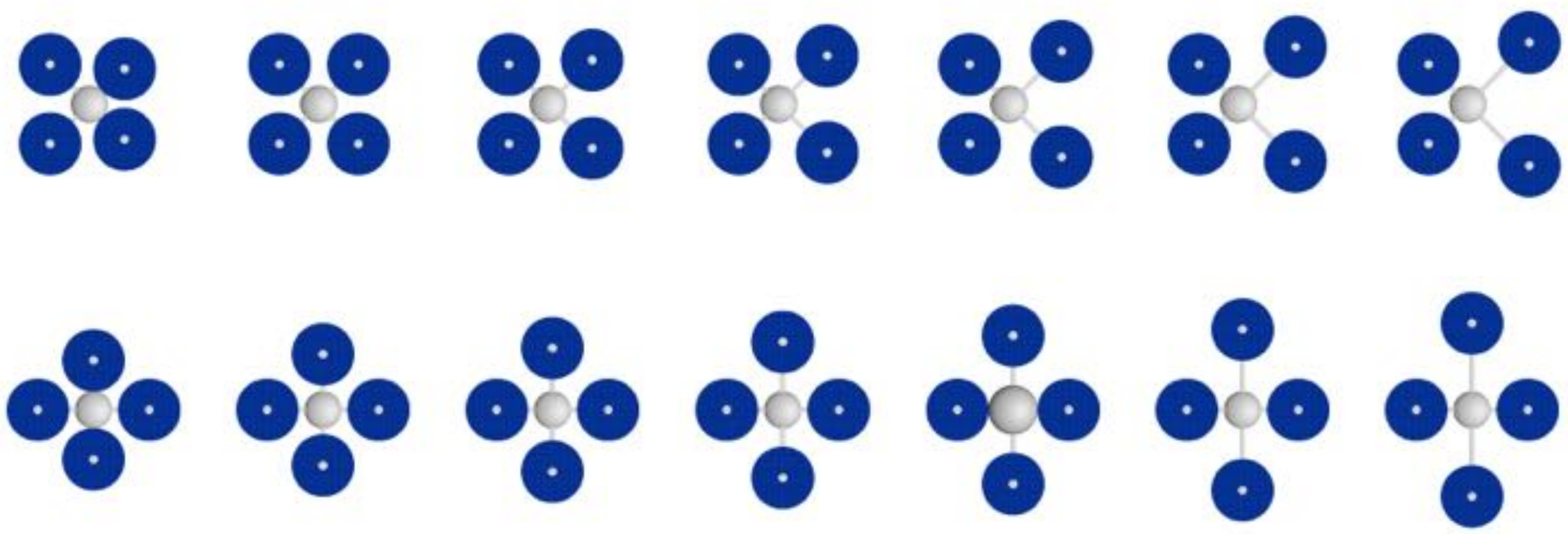


Parametric Quadcopter Study

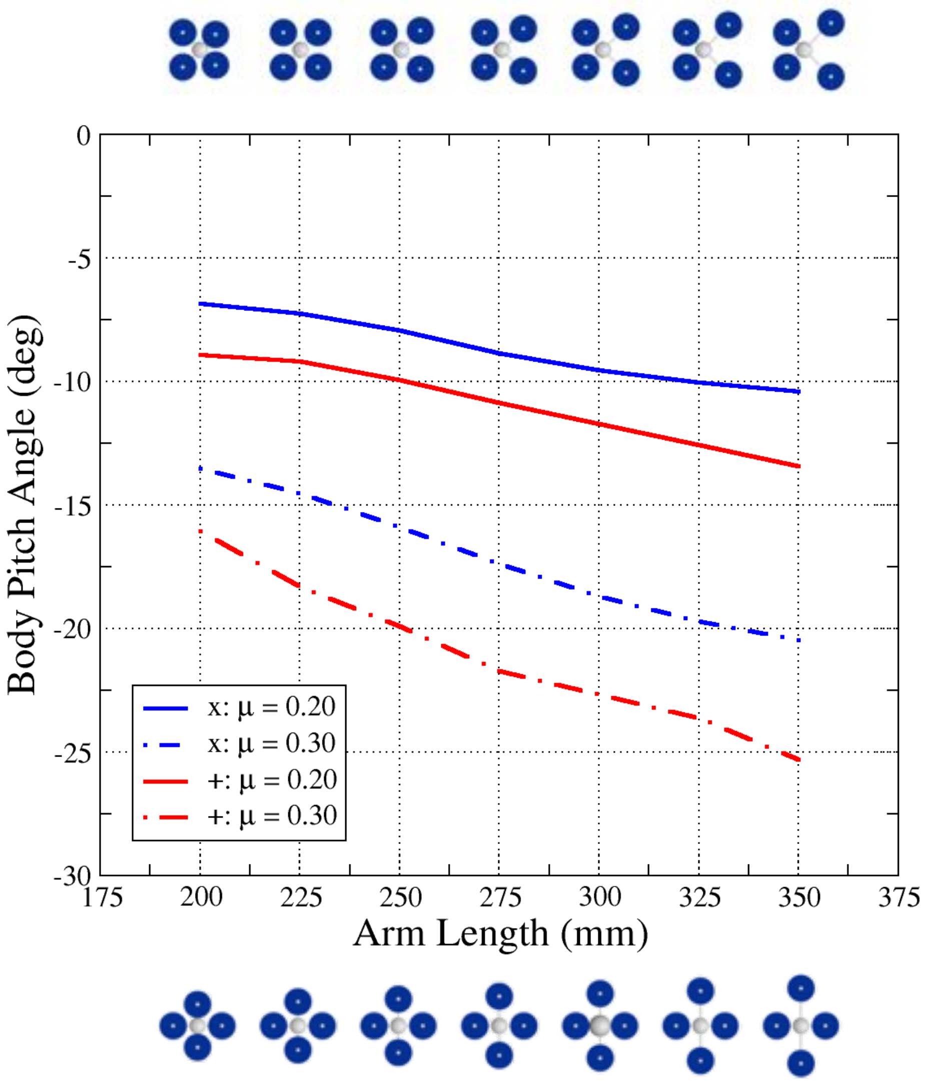
Investigate the effect of arm length for quadcopters at two speeds

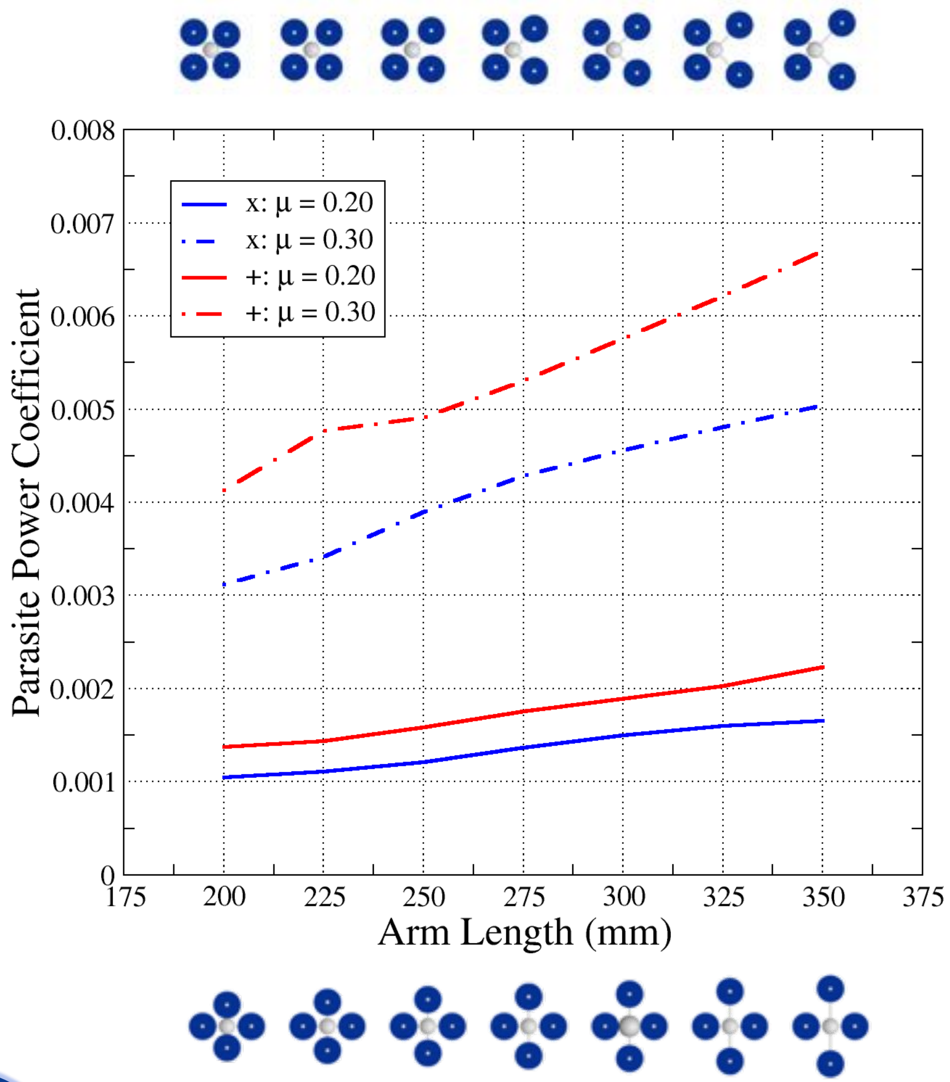
25mm steps between 200-350mm

Both x and + configurations

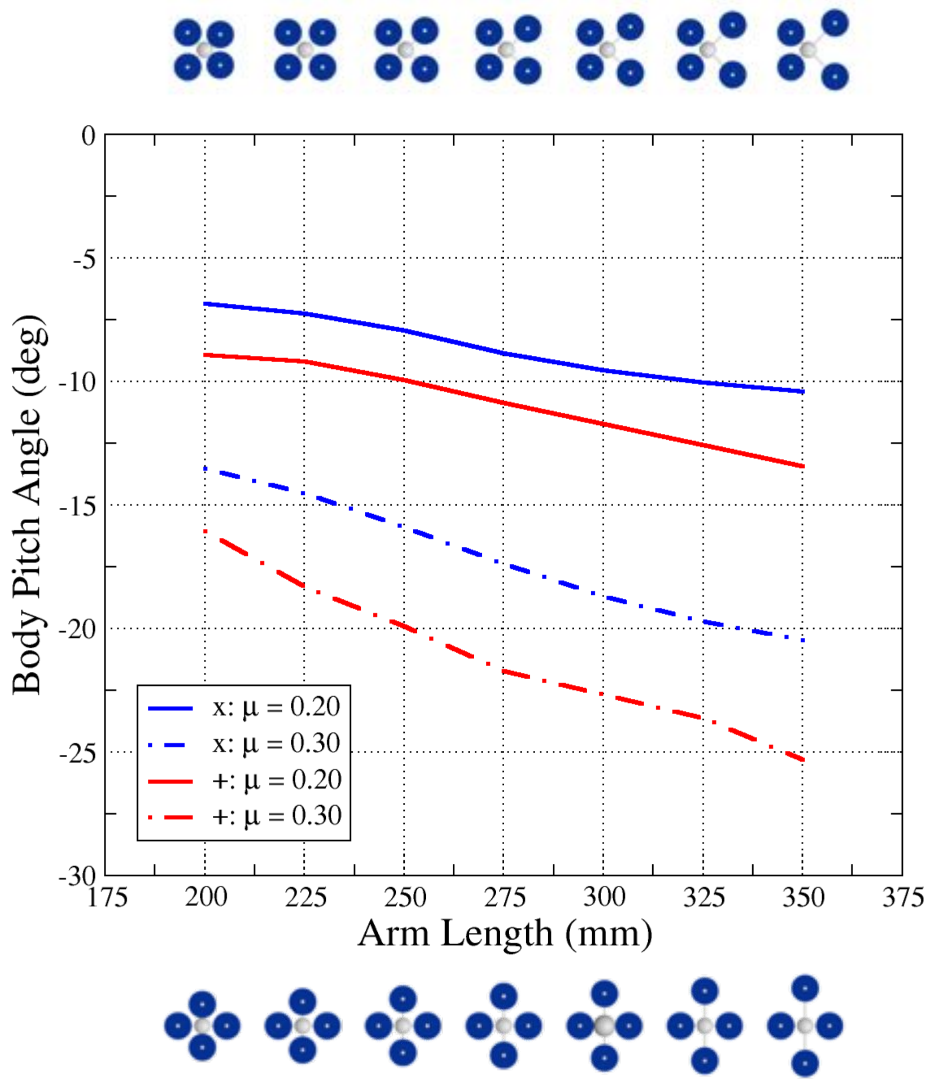


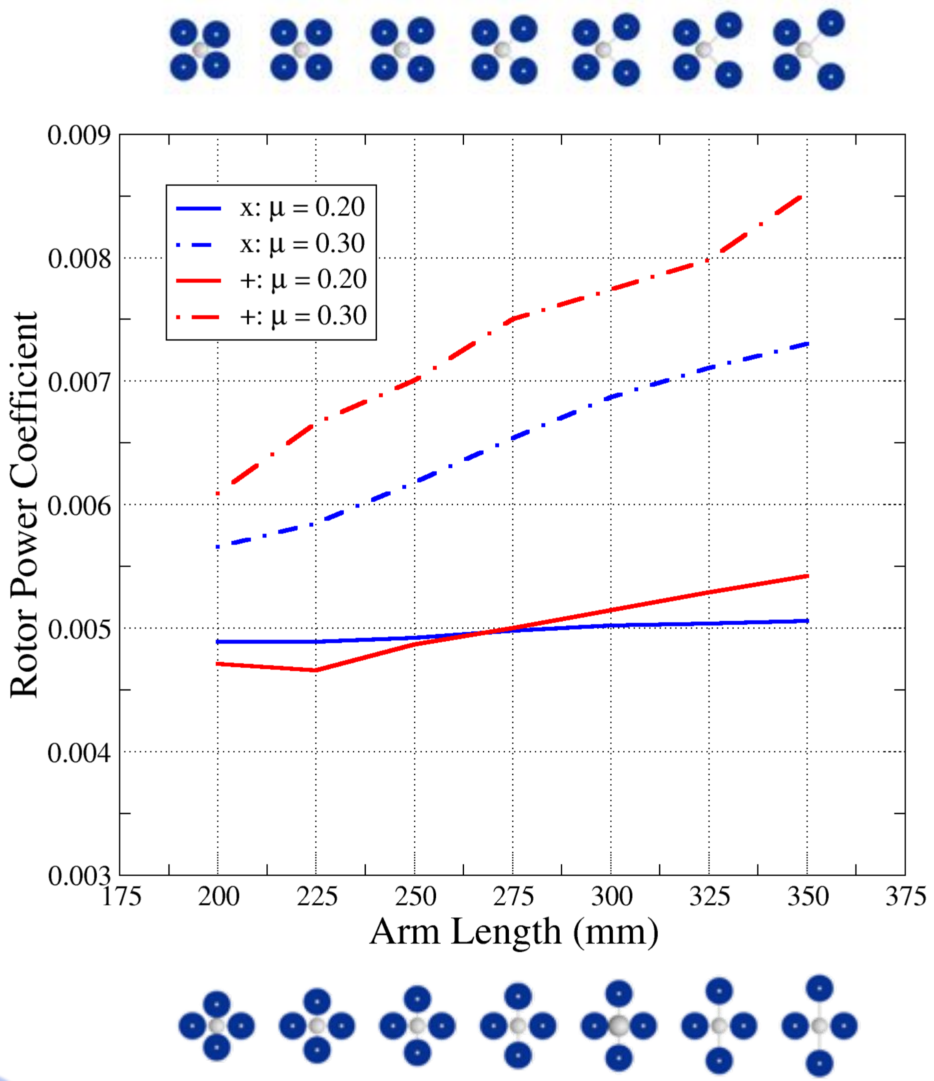
Parametric Quadcopter Study





Parametric Quadcopter Study





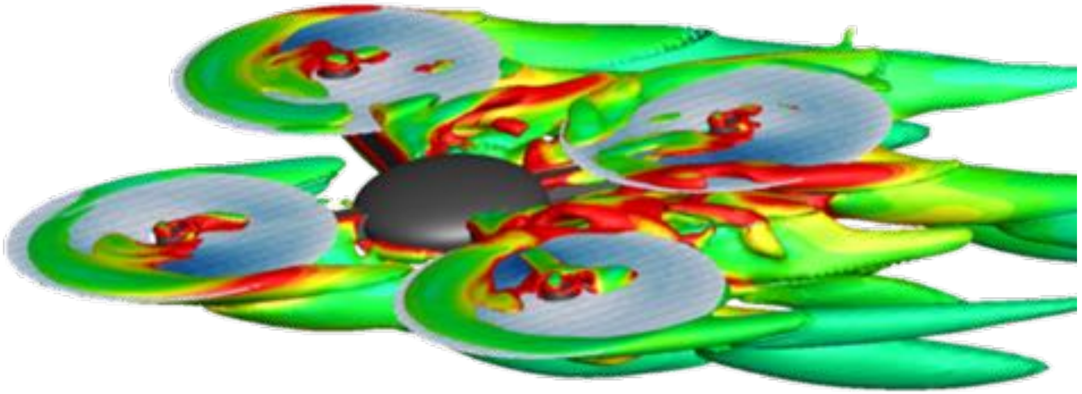
Parametric Quadcopter Study

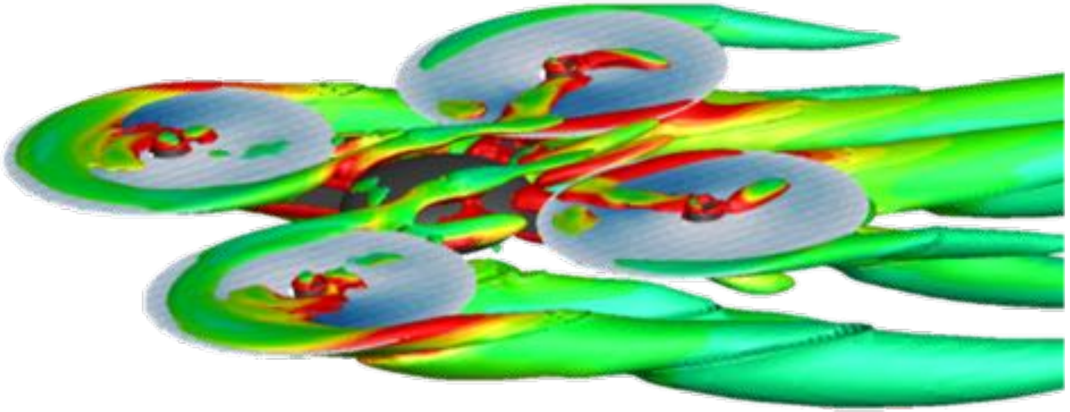
Trim algorithm for quadcopters works well

'x' configuration converges quickly (within 250 iterations after starting trim)

'+' configuration shows propeller-airframe interactions influence trim

Complete quadcopter simulations performed quickly at moderate computational cost (45 minutes on 40 Skylake cores)





Summary

Implemented a source-term rotor model for Cart3D using Cartesian hexahedra

Demonstrated good mesh convergence and linear parallel scalability

Performed validation study comparing to XV-15 data

Extended airfoil tables to capture low Reynolds number aerodynamic effects

Implemented trim algorithms for forward flight

Captured first order rotor-rotor interference effects

Performed “out-of-the-box” parametric quadcopter study

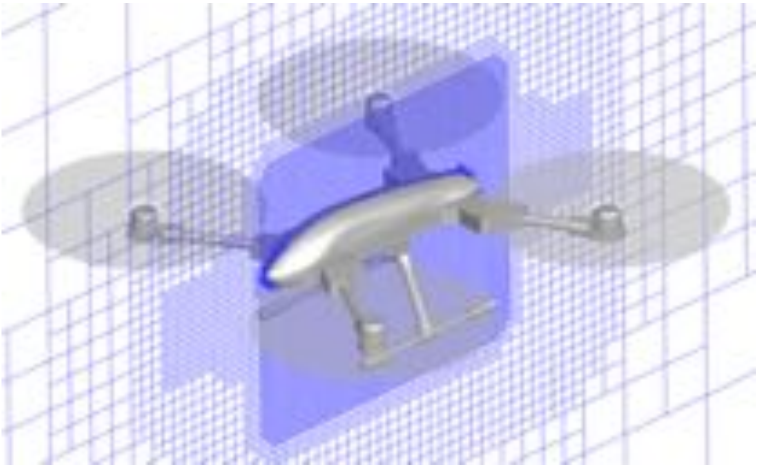
Outlook

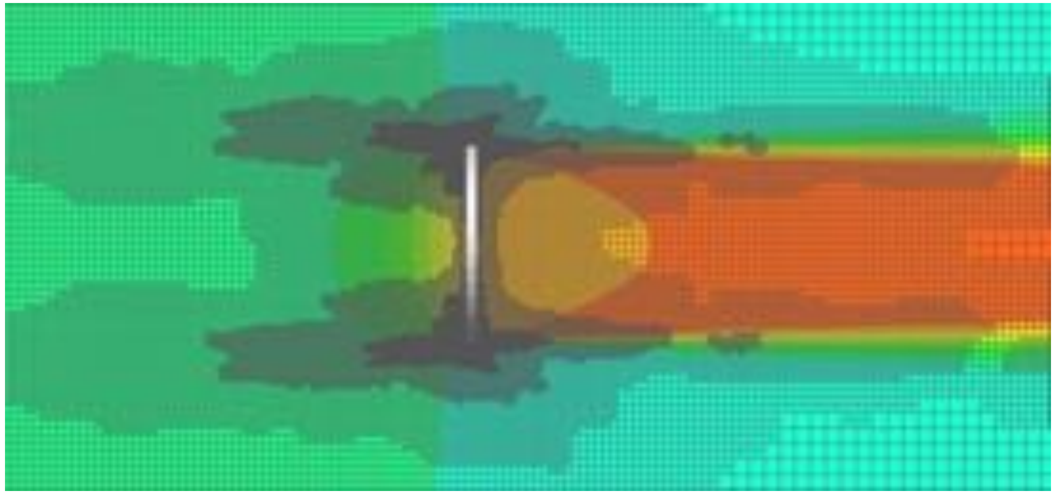
Validation of model with quadcopter wind tunnel data (Russell et al. AHS 2016)

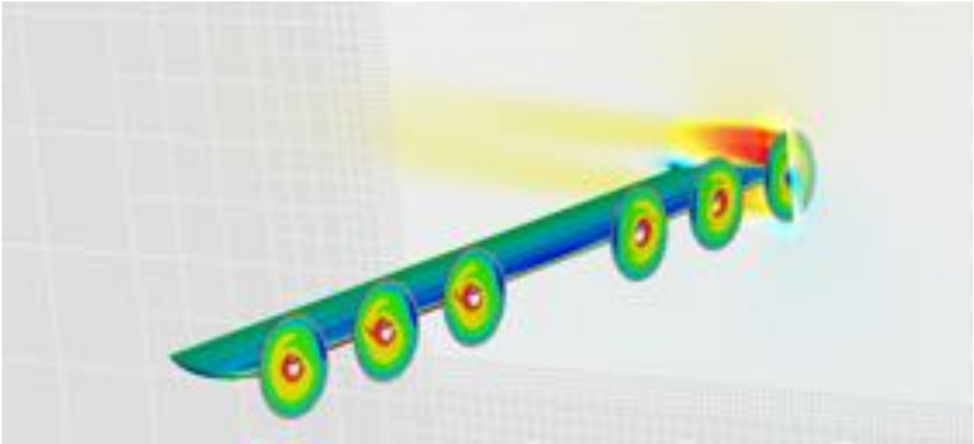
Detailed study of airfoil table requirements

Adjoint-based mesh refinement

Continued development of unsteady model







Acknowledgments

NASA Ames contracts NNA16BD60C

Transformational Tools & Technologies Project

Cart3D Development Team

Jasim Ahmad, Tom Pulliam, Gerrit Stich, Chris Silva (NASA Ames)

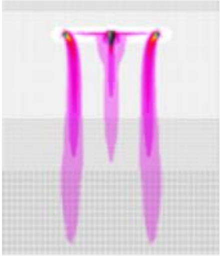
Computer resources were provided by the NASA Advanced Supercomputing Division's High-End Computing Capability Project

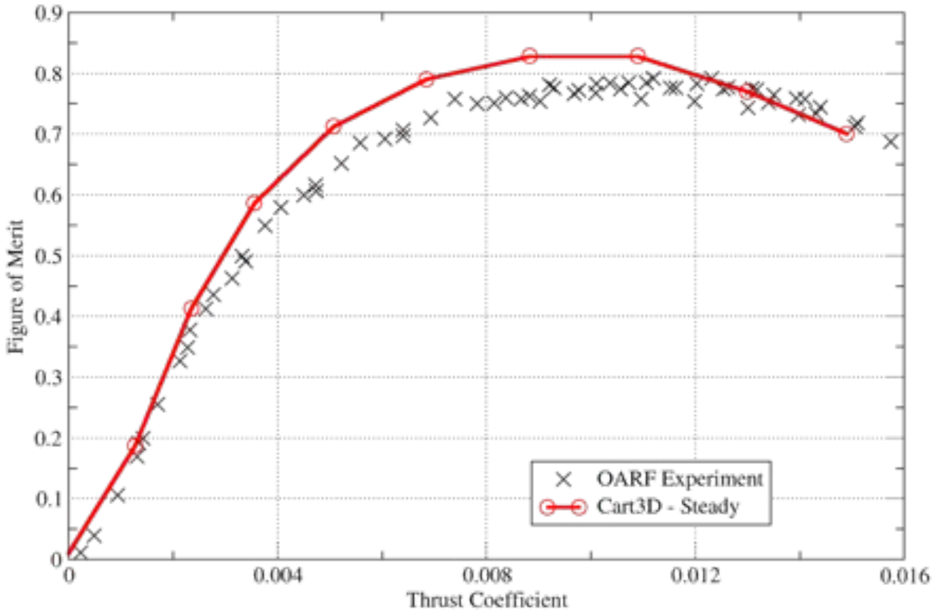
Questions?

Backup

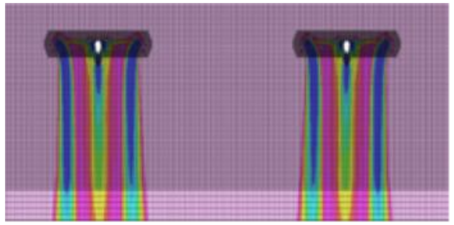
XV-15 Hover Simulations

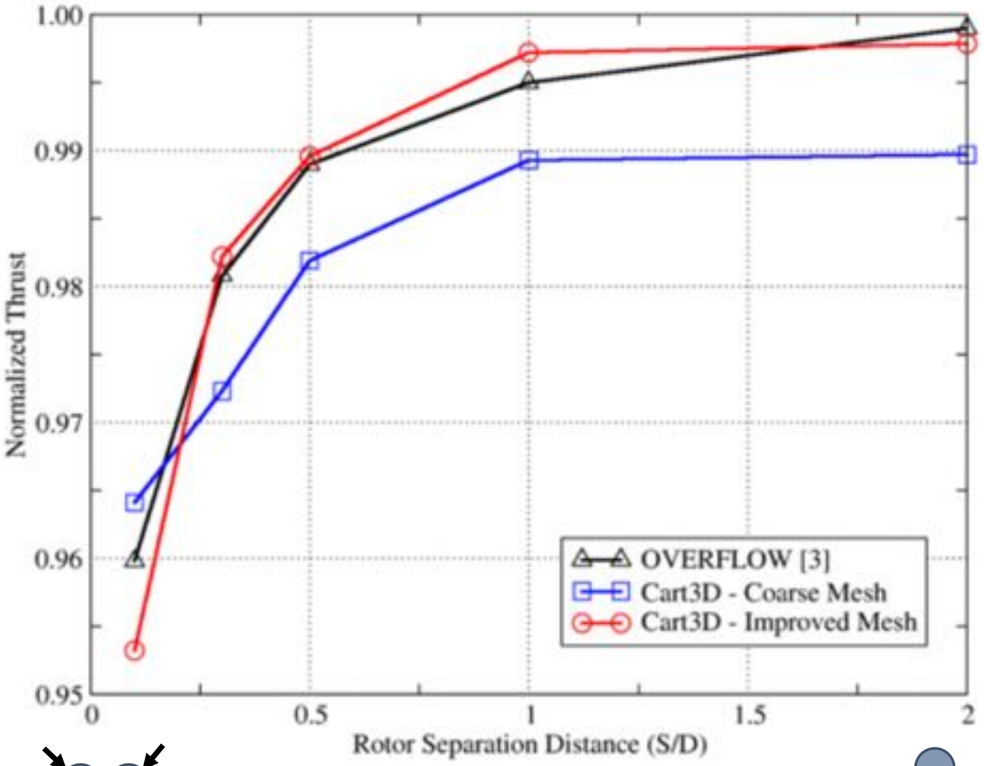
Isolated Rotor

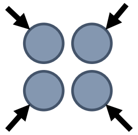


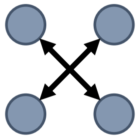


Quadrotor Separation

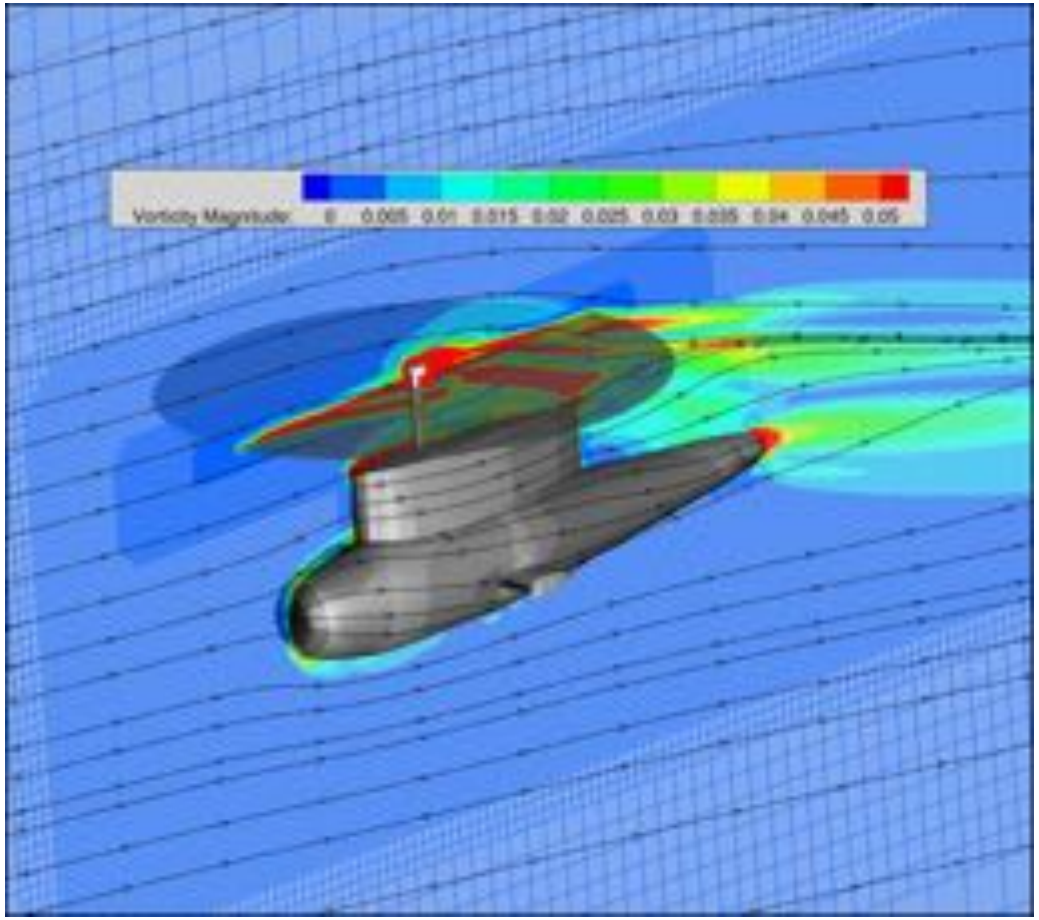


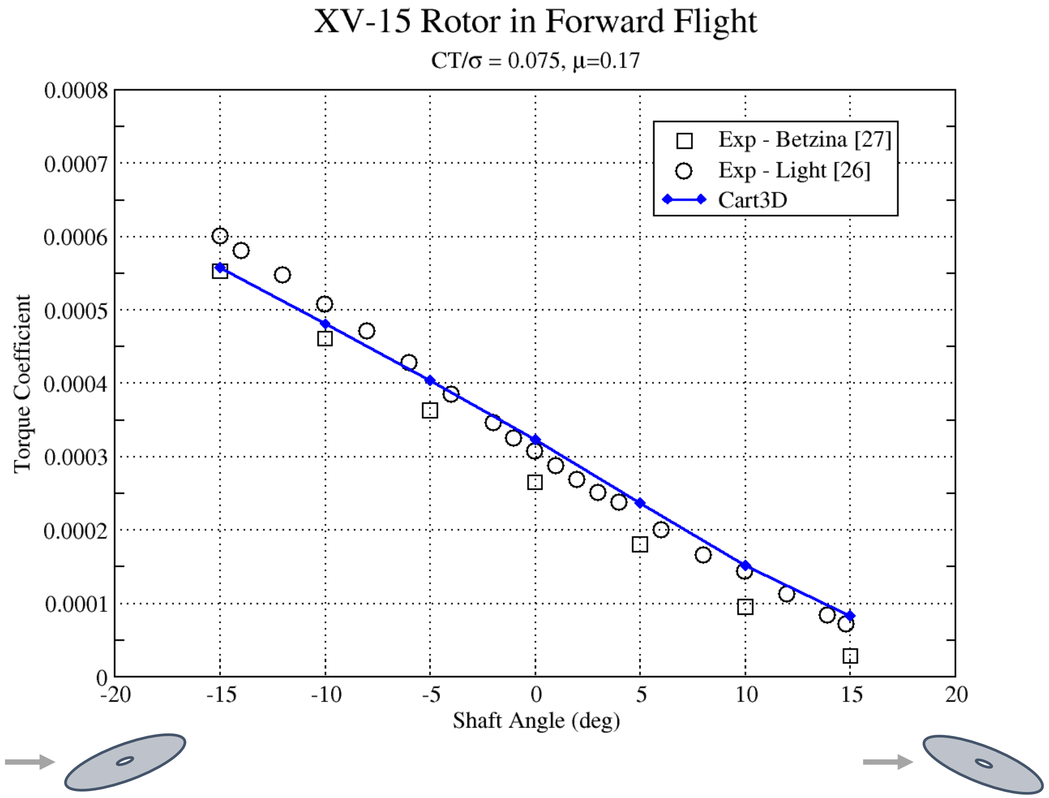




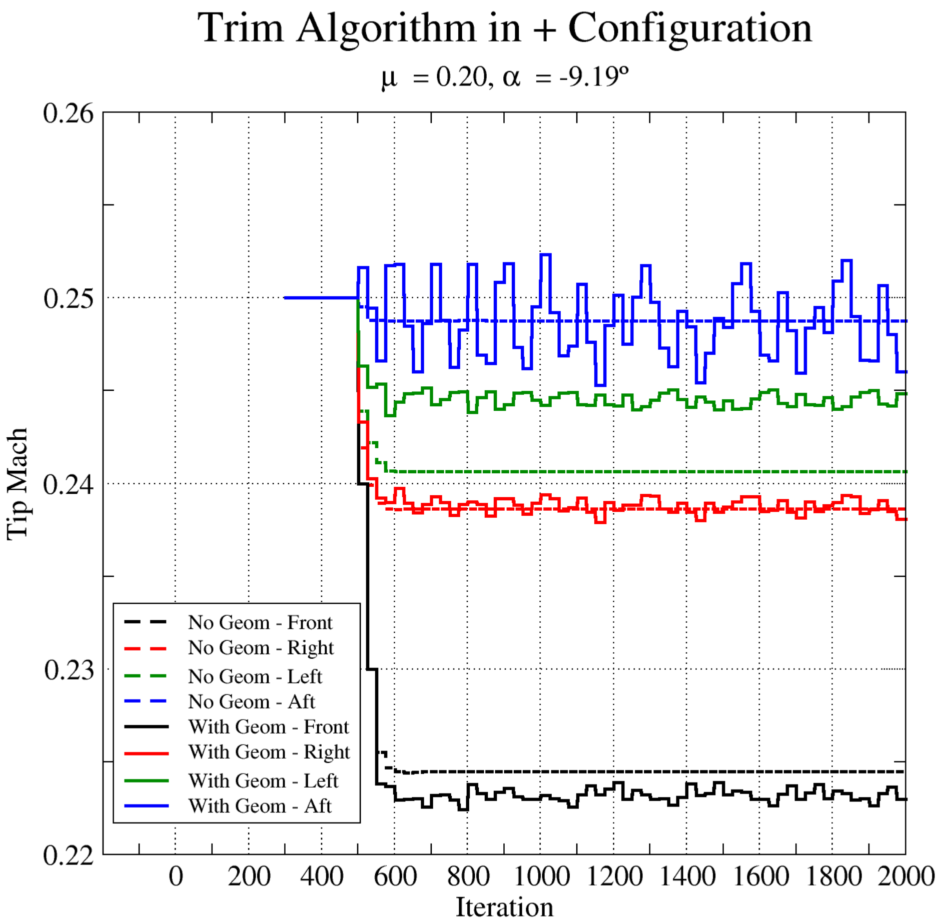


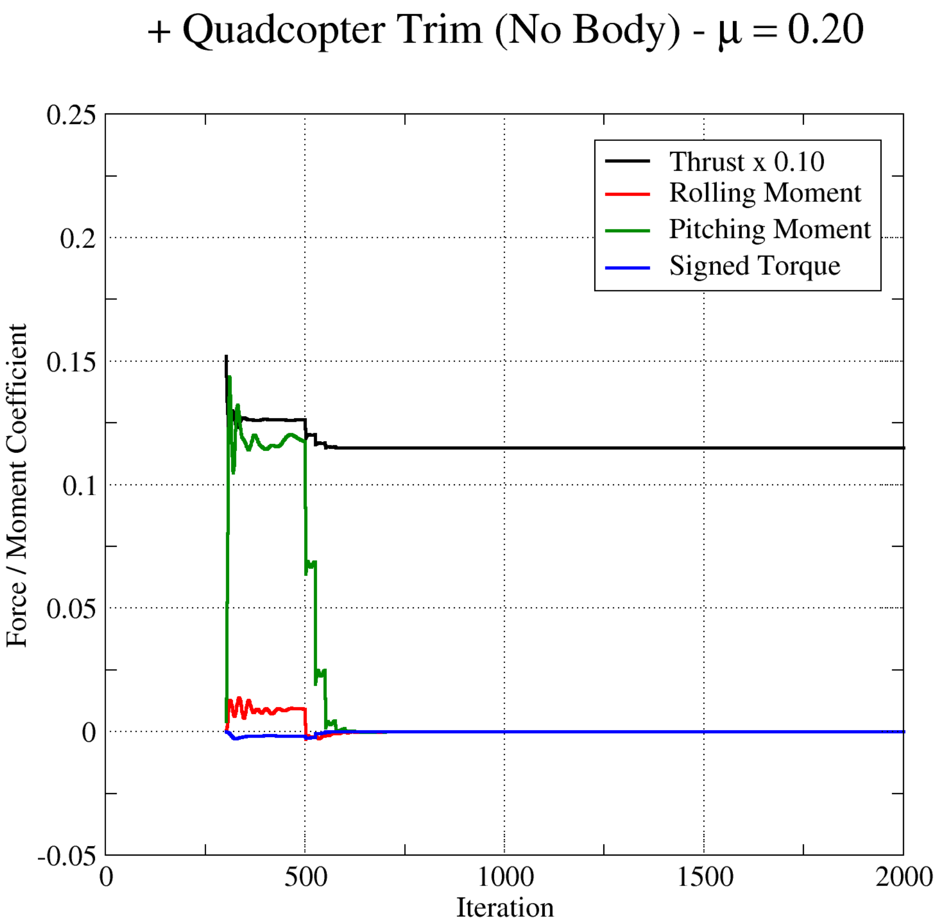
XV-15 Isolated Rotor Performance





Quadcopter Trim: + configuration (no body)





Parametric Quadcopter Study

Proposed trim algorithm for quadcopters generally works well

X configuration converges quickly (within 250 iterations after starting trim)

Airframe-propeller interactions can impair convergence of the trim algorithm

Complete quadcopter simulations performed relatively quickly at moderate computational cost